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ENVIRONMENTAL AND ENERGY QUALITY TECHNOLOGIES

Task Order 0005: Organic Finishing Technologies

Sub-Task Order 11: High Speed, Substrate Safe Specialty Coating Laser Stripping: Project: WP-2146

Alan Fletcher and Michelle Barga

Strategic Environmental Research and Development Program (SERDP)

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FINAL REPORT

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The objective of this Strategic Environmental Research and Development Program was to develop and evaluate environmentally friendly laser coating removal process for rapid and substrate-safe stripping of United States Air Force and Army specialty coatings. The efficacy of controlled coating removal, maximum temperatures realized by the underlying and surrounding substrates, speed of removal, and condition of remaining materials and surface were evaluated.

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SUMMARY

Objective: The objective of this Strategic Environmental Research and Development Program was to develop laser coating removal process for rapid and substrate-safe stripping of specialty coatings from United States Air Force aircraft as well as non-fielded Army specialty coatings. This was accomplished through the application of several new sensor technologies that have matured in the past few years, which enhanced the automated laser stripping for quick removal of the targeted coatings while leaving the substrate and underlying coatings unaffected and undamaged.

Technical Approach: In order to deliver a complete laser coating removal process that will effectively remove the specialty coatings without causing damage to the underlying coatings, materials, and substrates, a surface monitoring sensor based control system was developed, optimized within the limitations of the systems, and demonstrated for each material evaluated. The development of the laser coating removal process was achieved through the following tasks and activities:

- Task 1 – Determine Technical Requirements
    - Gather Baseline Information
    - Determine Performance Requirements
    - Complete Test Plan(s)
    - Complete Initial Cost Benefit Analysis
    - Complete Design Specifications for Sensors
- Task 2 – Optimization for Specialty Coating Removal
    - Prepare Test Panels
    - Perform Preliminary Laser Testing
    - Complete Sensor and Laser Control Development
    - Perform Optimization Testing
    - Perform Optimization Test Analysis (Go/No Go Decision)
- Task 3 – Evaluation Testing
    - Perform Evaluation Laser Testing
    - Perform Evaluation Material Testing
    - Complete Final Cost Benefit Analysis
    - Complete Air and Wipe Sampling for Chromium Analysis

Results: Laser coating removal of various coating stack-ups were evaluated from three different weapon systems. The removal goals were accomplished successfully for some of the coating stack-ups. For other coatings, the removal goals were not completely accomplished, but were accomplished to the best of the sensor's current control abilities. For those scenarios, the majority of the upper coating layers could be removed; but the laser removal process was unable to leave the base coating layer, above the substrate, completely intact. Further refinement of the sensors and control is recommended, as well as additional optimization testing prior to implementation of a robotic laser coating removal system for full aircraft coating removal applications.

For most of the laser coating removal testing, the temperatures recorded during the laser removal did not exceed the 250 degrees Fahrenheit (°F) maximum temperature requirement. However, one maximum temperature recorded was 352°F on a panel with exposed thermocouples. The substrates did not appear to have any thermal damage, but this would need to be confirmed through substrate material testing.

The laser removal strip rates were different for the various coating stack-ups and coating removal goals. The strip rates ranged between 0.15 minutes per square feet (min/ft^2) and 9.7 min/ft^2. The strip rates for one weapon system were equal to or faster than targeted strip rate goals. However, the strip rate results for the other weapon systems were equal to or slower than the targeted strip rate goals.

The material test results met or exceeded the control sample results indicating no impact of the laser strip process to coating properties such as adhesion, cohesion, elasticity, and special characteristics. There was some degradation in the coating tensile and elongation; however, the weapon system program office will need to determine if this decrease in within allowable limits.

Expected Benefits: Laser coating removal is an environmentally-friendly method that does not produce a secondary waste stream, only the ablated coating will remain and will be captured in a high-efficiency particulate air filter system – reducing or eliminating worker exposure to hazardous materials and eliminating the hazardous waste streams associated with wheat starch, chemical strippers and hand sanding. Additionally, the laser coating removal process is an automated process that will reduce labor costs and long-term impacts and costs associated with worker damage to hands, wrists, and other joints caused by the ergonomically challenging manual and media blasting methods currently used for specialty coating removal. Finally, the laser coating removal process has the potential to increase the strip rates above the current coating removal methods without damaging the composite substrates. Laser coating removal also has the potential for selective coating removal.

1.0 INTRODUCTION

The United States Air Force Research Laboratory (AFRL)/Materials Integrity Branch (RXSS) has led a four-year Strategic Environmental Research and Development Program (SERDP) project WP-2146, "High-Speed, Substrate Safe Specialty Coating Laser Stripping," to develop a laser coating removal process for large area stripping of specialty coatings from United States Air Force (USAF) aircraft, as well as United States Army (herein referred to as Army) specialty coatings. This effort represents a collaborative effort involving the weapon system program offices (SPOs); Structural Engineers; the Army Research Laboratory (ARL); Ogden Air Logistics Complex (OO-ALC) engineers and representatives; Concurrent Technologies Corporation (CTC); Northrop Grumman Corporation; and Materials and Process Solutions LLC.

This Final Report captures the technical results of the four-year long SERDP project WP-2146. Specifically, this Final Report provides an explanation of the activities that were accomplished over the life of the project, the technical results and discussion, and the conclusions and implications for future research/implementation of an automated laser robotic coating removal system for large area specialty applications.

1.1 Objective

The SERDP statement of need (SON), WPSON-11-05, called to develop a large-scale, non-media, non-chemical process for removing specialty coatings and treatments from three Department of Defense (DoD) weapon systems without causing damage to the underlying substrates (i.e., composite, aluminum and titanium) or treatments below the specialty coatings. To address this SON, a robotic laser coating removal solution was proposed and accepted for development and investigation as SERDP Project WP-2146.

Therefore, the objective of this SERDP Project WP-2146 was to develop a robotic based laser coating removal process to achieve the goal of selective removal of specialty coating systems without causing thermal or other damage to underlying coatings, materials, and substrates.

1.2 Approach

Laser coating removal has shown applicability to several specialty coatings and treatments during previous preliminary laser removal investigations. However, in order to deliver a complete laser coating removal process that will effectively remove the specialty coatings without causing damage to the underlying coatings, materials, and substrates, a control system would need to be developed. For this SERDP project WP-2146, a surface monitoring sensor based control system was developed, optimized within the limitations of the systems, and demonstrated for each specialty material evaluated.

The development of the laser coating removal process was achieved through the following tasks and activities which will be discussed in Section 3.0.

- Task 1 – Determine Technical Requirements
    - Gather Baseline Information
    - Determine Performance Requirements
    - Complete Test Plan(s)
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    - Complete Design Specifications for Sensors
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2.0 BACKGROUND

The need to develop a robotic based laser coating removal process is driven by several issues including environmental and ergonomic issues. These issues are outlined below along with background information on laser coating removal and the resources used from other related projects.

2.1 Environmental Issues

Modern military aircraft utilize a complex buildup of materials to impart rain erosion, electrical bonding, adhesive bonding, chemical attack resistance and other special characteristics while providing corrosion protection. The materials used for these purposes are designed to be permanent treatments, and are very difficult to remove when one or several of the layered materials fail or are ready for removal for periodic inspection and/or replacement.

Standard coating removal methods include chemical strippers, media blasting (i.e., wheat starch, plastic media), hand sanding, and manual skiving. These current removal methods can be costly, time consuming, labor-intensive, produce secondary hazardous waste streams, and result in undesirable environmental and worker conditions. The wastes that are associated with material removal using abrasive blast media for blasting operations include the disposal of the spent media. The wastes that are associated with material removal using chemical strippers include disposal of chemical soaked rags, mats, and personal protective equipment (PPE), as well as chemical soaked coating sludge. Current depaint efforts for a bomber size aircraft have reported using approximately 330 gallons of chemical removers per aircraft, generating approximately 6,000 pounds of contaminated chemical associated waste per aircraft, and using approximately 35,000 pounds of abrasive blast media per aircraft.

Large quantities of waste (hazardous and non-hazardous) are commonly generated from these depot-related aircraft depaint activities, and, depending on the removal process, are subjected to scrutiny under environmental regulations such as the Clean Water Act, Clean Air Act, and Resource Conservation and Recovery Act (RCRA). The RCRA directly regulates disposal of wastes generated by depainting activities. The RCRA regulates how and where depainting waste can be disposed and transported as well as any future liabilities resulting from environmental damage.

2.2 Ergonomic Issues

The current coating removal methods used for specialty coating removal, specifically manual removal and media blasting, are ergonomically challenging methods that cause damage to workers' hands, wrists, and other joints.

2.3 Laser Coating Removal

Laser coating removal is an alternative technology to the current removal methods that are used to remove coatings from large off-equipment aircraft components and full aircraft outer mold

line areas. The laser removal process will generate no secondary waste stream; the only waste generated will be the removed coating debris that will be captured in a high-efficiency particulate air capture system to manage the cleanliness and air standards of the process area.

When laser coating removal is combined with robotics to create an automated process, the system should eliminate or reduce the labor-intensive, ergonomically damaging environment that workers are subjected to under the current coating removal processes.

Most of the previous laser coating removal efforts have been targeted for the removal of standard primers and topcoats (i.e., MIL-PRF-23377 primer and MIL-PRF-85285 topcoat) because they are in the highest use on USAF legacy aircraft. Advancements and maturation of the following key technologies over the last few years have allowed for quick and safe coating removal of standard paint systems from aircraft substrates:

- High powered fiber laser technology – ablates the coating material
- Scanner technology – rapidly manipulates the laser beam back and forth
- Sensor technology – provides real-time control of the level of coating removal

The same high-powered laser coating removal technologies selected and/or developed for the standard paint systems were leveraged for the removal of specialty materials under this SERDP project. The laser coating removal process and parameters that were developed under this program will be amenable to automated operations such as full aircraft surface coating removal or coating removal of large off-aircraft components such as flight controls.

2.3.1 Leveraged Laser Technology

There are three major types of lasers used for coating removal:

- Solid state lasers (such as Neodymium:Yttrium-Aluminum-Garnet [Nd:YAG])
- Gas Lasers (such as carbon dioxide [CO_2])
- Semiconductor Lasers (such as diode, fiber, and disc)

Under previous efforts for the USAF Laser Coating Removal Program, four laser systems (listed below) were initially considered for full aircraft stripping applications.

- Nd:YAG laser (1064 nanometer [nm] wavelength)
- CO_2 laser (10,600 nm wavelength)
- Fiber-delivered diode (808, 915, 940, or 976 nm wavelength)
- Fiber laser (1070 nm wavelength)

The Nd:YAG and fiber-delivered diode lasers were eliminated from selection due to their low output powers which would not be sufficient for large area removal. The high-powered fiber laser was selected for the USAF Laser Coating Removal Program full-aircraft effort based on a trade-off analysis of the fiber verses CO_2 laser. The main limitation of the fiber laser verses the CO_2 laser is its high absorption with aluminum, but this has been mitigated with sensors and

control systems. However, the high-powered fiber laser was selected instead of the CO_2 laser for the reasons listed below.

- Lightest in weight
- Fiber optic beam delivery
- Higher beam quality
- High irradiance levels
- Lower long term maintenance and operating costs

Fiber lasers have several advantages. Fiber lasers have a monolithic, entirely solid state, fiber-to-fiber design that does not require mirrors or optics to align or adjust. These features make fiber lasers easier to integrate and operate in industrial applications. Fiber lasers are typically smaller and lighter in weight than traditional lasers, saving valuable floor space. While CO_2 lasers can be delicate due to the precise alignment of mirrors, fiber lasers are more rugged and able to perform in variable working environments. These qualities permit fiber laser systems to be transported easily. Another advantage associated with the use of fiber lasers is their lower operational cost and environmental impact when compared to other industrial lasers. Fiber lasers have a higher electrical efficiency, 30% as compared to the 5-10% efficiency achieved by carbon dioxide lasers, require less cooling input, and have no consumables such as gases or lamps.

Figure 1 shows the fiber laser beam delivery methodology. High power fiber lasers are created from arrays of active optical fibers that are doped with Ytterbium. Each of these fibers uses a single emitter semiconductor diode as the light source to pump the active fibers. The laser beam emitted is contained within the fibers and delivered through an armored flexible cable to an integrated flexible output fiber. These fibers allow for an extremely bright light from a very small core, thus making possible the production of kilowatt class output with excellent beam quality. The fiber laser is modular, built from multiple laser units, each one generating hundreds of watts of output power. This also allows the laser system to incorporate reserve modules and power margins. If something should happen with a regular fiber laser module it will shut off and allow the redundant module to start automatically, leaving the laser with no output power loss.

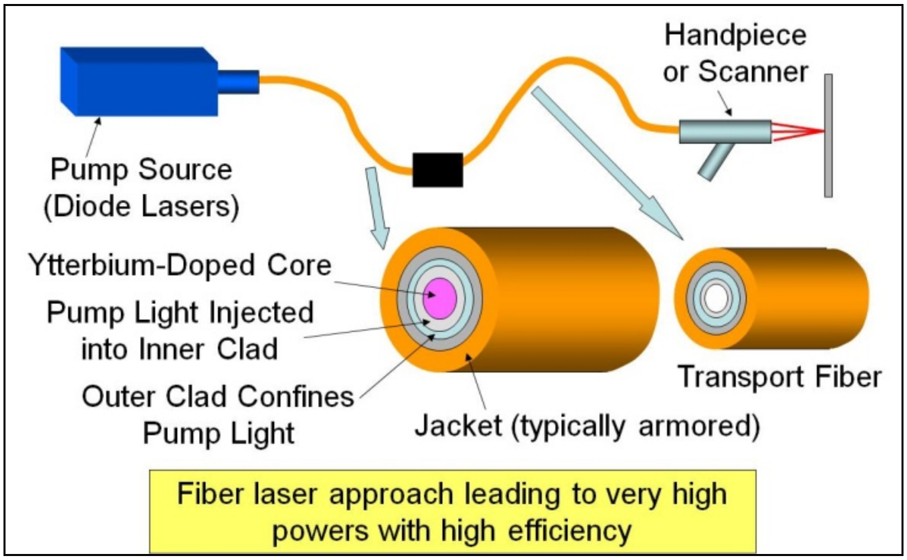

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Figure 1. Fiber Laser Beam Delivery Method

2.3.2 Leveraged Laser Control Systems

This project leveraged spectral control systems and color recognition systems that were developed for previous NdYag laser systems. The spectral system previously developed was total inadequate for this effort since it could only differentiate major chemical groups and was not able to have fast enough recognition to in-situ control the laser. In addition, the previous spectral senses required an extra laser source to make determinations on the chemical composition of the material being ablated. The needed improvements to the current state-of-the-art spectral senses was 1). Real time material identification before each laser pulse. 2). Utilize the laser plume to analyze material 3). Be able to differentiate within general material groups (i.e. different kinds of epoxies). Figure 2. shows the current system.

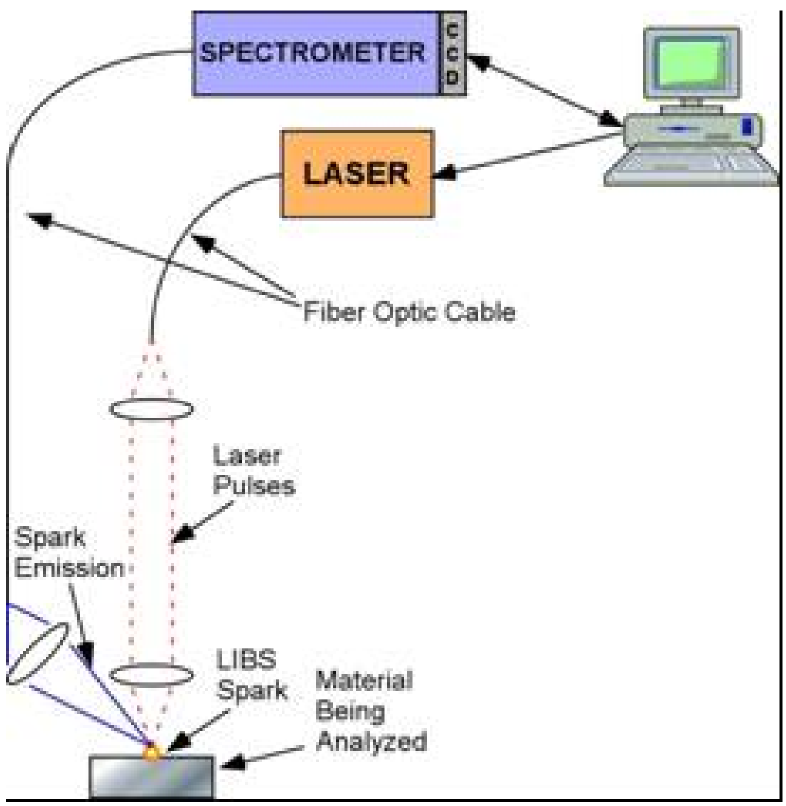

Figure 2. Laser Induction breakdown Spectroscopy

The color recognition sensors utilized by past efforts were limited to major color groups and very limited to differentiating between blue and green, grey and black, etc. Due to the closeness of the colors utilized for the different layers of materials needing to be removed, the color recognition system needed much refinement. Figure 3 shows the type of color differentiation needed.

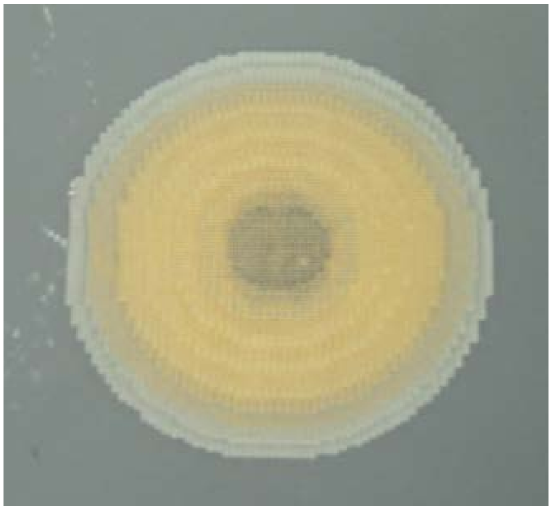

Figure 3. Typical Color Differentiation Needed

Previous laser systems did not utilize thickness sensors. This effort in order to partially remove layers needed to develop an in-situ real time thickness sensor that could measure within 0.0005 inches the thickness of the coating remaining. There was a system under development to measure the wet film thickness of coatings being applied. This system utilized terahertz signals to measure how much material had been applied. This project started with this terahertz system and further developed it for use with the laser to measure dry film thickness. Figure 4 shows the current wet film thickness sensor that is being developed.

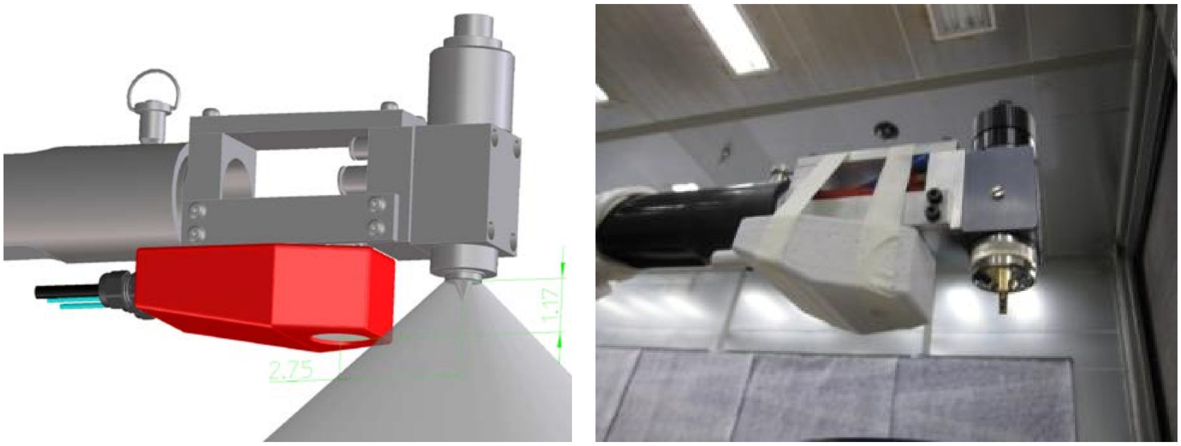

Figure 4. Terahertz Thickness Sensor

2.3.3 Leveraged Laser Equipment Set-Up in Enclosed Test Cell

This project leveraged and utilized the existing USAF owned fiber laser coating removal system housed in a test cell enclosure, shown in Figure 5, at the CTC Environmental Technology Facility (ETF) in Johnstown, PA.

Figure 5. Laser Coating Removal System Test Cell at CTC

The fiber laser coating removal system uses a 6 kilowatt (kW) laser system (model: IPG YLR-6000) manufactured by IPG Photonics, Inc, as shown in Figure 6.

Figure 6. 6 kW Fiber Laser

The laser beam is delivered via a fiber cable to the Scanlab America Inc. optical beam scanner that delivers the laser beam to the surface. The beam spot size is a 3 millimeter (mm) x 5 mm

ellipse that is rastered over a 140 mm wide beam path. Both the laser and scanner are integrated onto a 6-axis FANUC robotic arm. A photo of the integrated system within the test cell is shown in Figure 7.

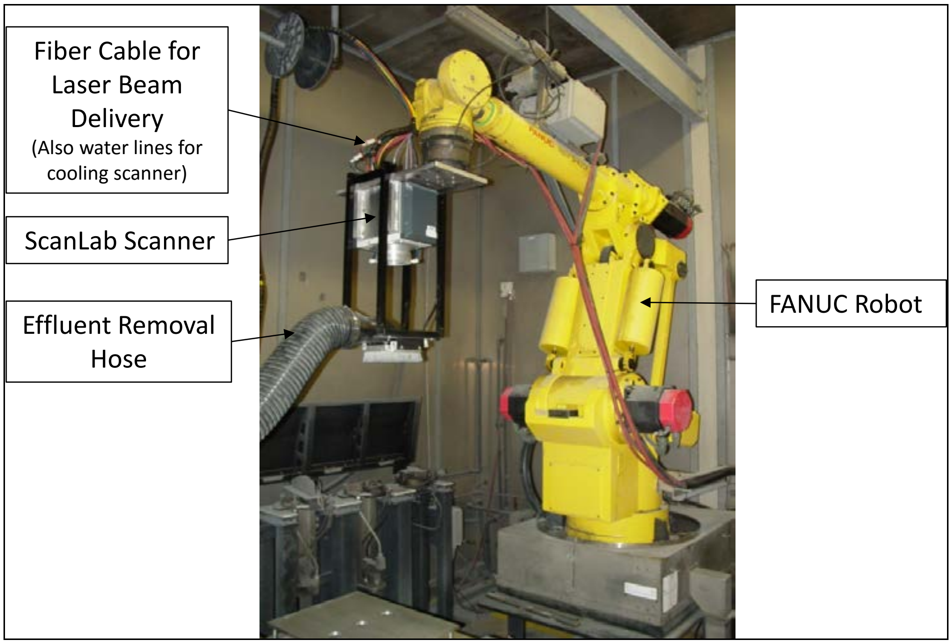

Figure 7. Fiber Laser Coating Removal System at CTC eeded

Effluent removal is accomplished by using a TEKA Filtercube2 vacuum system (herein referred to as TEKA) designed for weld fume extraction. The system utilizes two pleated cartridge filters for capturing the effluent removed and a bed of activated carbon for extraction of fumes. The dust collection efficiency of the cartridge filters is listed at greater than 99.99 percent with a Minimum Efficiency Reporting Value 10 rating. The cartridge filters are automatically back-pulse cleaned with compressed air. An Aercology FDV-600 Dust/Mist Filter is used to supply fresh air into the fiber laser test cell. The used air from the test cell is ventilated through the facility roof.

2.3.4 Leveraged Full Aircraft Automated Robotic Laser Coating Removal System (ARLCRS) Technology

This project also leveraged the Full Aircraft Advanced Robotic Laser Coating Removal System (ARLCRS) prototype developed under the AFRL Contract FA8605-09-D-5601, Task Order 0001 “Advanced Laser Coating Removal Development,” as well as the Full Aircraft ARLCRS production unit developed under the National Defense Center for Energy and Environment Contract W91ZLK-10-D-0005, Task 0793 “Develop and Demonstrate Full Aircraft Laser Coating Removal in a Production Environment,” and transitioned to OO-ALC in Utah, to replace the existing coating removal methods.

The Full Aircraft ARLCRS, shown in Figure 8, is made of several subsystems that are integrated together into an automated system. The major components include the robotic base, laser, laser process control, and ancillary equipment.

Figure 8. Advanced Robotic Laser Coating Removal System (ARLCRS)

This system also uses a 6 kW fiber laser system manufactured by IPG Photonics (refer to Figure 3) and optical beam scanner manufactured by ScanLab America Inc. The laser power, delivered to the surface by the scanner, is controlled based on feedback from surface monitoring sensors. The surface monitoring sensors are used to control the extent of coating removal and to automatically adapt the robotic processing of the surface based upon the surface conditions. This is completed through the combined capabilities of spectral emission monitoring sensors and surface monitoring sensors with the color recognition capabilities that are used to produce the 3-D surface image.

The supervised autonomous robotic base of the system was developed by the National Robotics Engineering Center (NREC). This robot is based on a commercially available mobile platform coupled with an industrial robotic arm and the autonomy control systems that NREC has previously developed and demonstrated for other applications. The system is designed to operate as a supervised semi-autonomous robotic system to optimize the following parameters.

- **Scalability:** The system is designed to scale from one to many robots to handle aircraft of various sizes. The motion of multiple robots will be coordinated automatically.
- **Efficiency:** The system will automatically plan for the most efficient way to strip the paint for a particular aircraft, based on the 3-D model of the aircraft and the number of available robots. In addition, the system also reduces unnecessary passes by discriminating surfaces that have been stripped completely in real-time. Furthermore, the system also allows virtual masking to reduce the labor needed to mask certain areas of the aircraft that should not be exposed to the laser.

- **Better Quality Assurance/Quality Control (QA/QC):** The robotic paint-stripping is designed to be more repeatable than the currently used automated or manual systems. In addition, the system captures a full 3-D texture map model of the aircraft that can be used for QA/QC.
- **Safety:** Multiple layers of safety systems are used to ensure the safe operation of the robotic system. These safety systems include real-time obstacle detection, automated collision check, and extensive built-in test for all the critical parts of the system.
- **Maintenance:** The system is designed to use as many commercial-off-the-shelf (COTS) components as possible to simplify the long term maintenance and manufacturability of the system.

Each robot in the system contains several key subsystems. The first subsystem is the mobile base which is a COTS heavy duty side-lift with a vertical boom that is manufactured by Hubtex and shown in Figure 9. These COTS bases are fully multi-directional vehicles that are electrically powered and have lift height and weight capacities that are sufficient for reaching all areas of the aircraft.

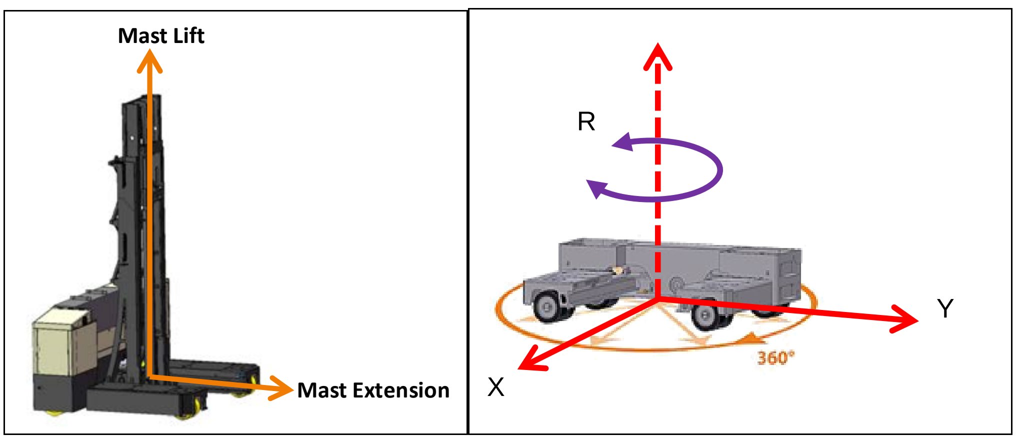

Figure 9. Omni-Directional Mobile Base Platform

The next subsystem is the COTS robotic arm manufactured by KUKA an example of which is shown in Figure 10. As part of the detailed system design, a thorough analysis of the reach, mechanics, and control possibilities of multiple commercially available robotic arms was performed prior to selection of KUKA manipulators.

Figure 10. Robotic Arm Manipulator

The final subsystem for the robotics is the real-time perception sensors. Several different types of sensors are used to help position the laser head accurately with respect to the aircraft, assess the condition of the surface (e.g., bare metal detection), and detect obstacles in the path of the mobile base and manipulator. A combination of scanning laser detection and ranging laser line striper and color cameras are utilized to produce a perception system capable of creating high precision three dimensional surface maps in real time. The data accuracy range for this system is <1 millimeter (mm) while collecting over 6000 data points per second.

Overall the system design allows the system to be operated by a minimum number of operators. Two operators are sufficient to operate a system with 2-4 robots. The operator control station is designed to allow the system operators to monitor the overall operation, and will alert the operators if it detects malfunctions or issues with the operation.

3.0 TECHNICAL ACTIVITIES ACCOMPLISHED

The development and evaluation of the laser coating removal process for specialty coating removal was achieved through the technical activities as shown in Figure 11. These activities were broken out into three main tasks which are outlined further in Sections 3.1 – 3.3.

- Task 1 – Determine Technical Requirements
- Task 2 – Optimization for specialty Coating Removal
- Task 3 – Evaluation and Material Testing

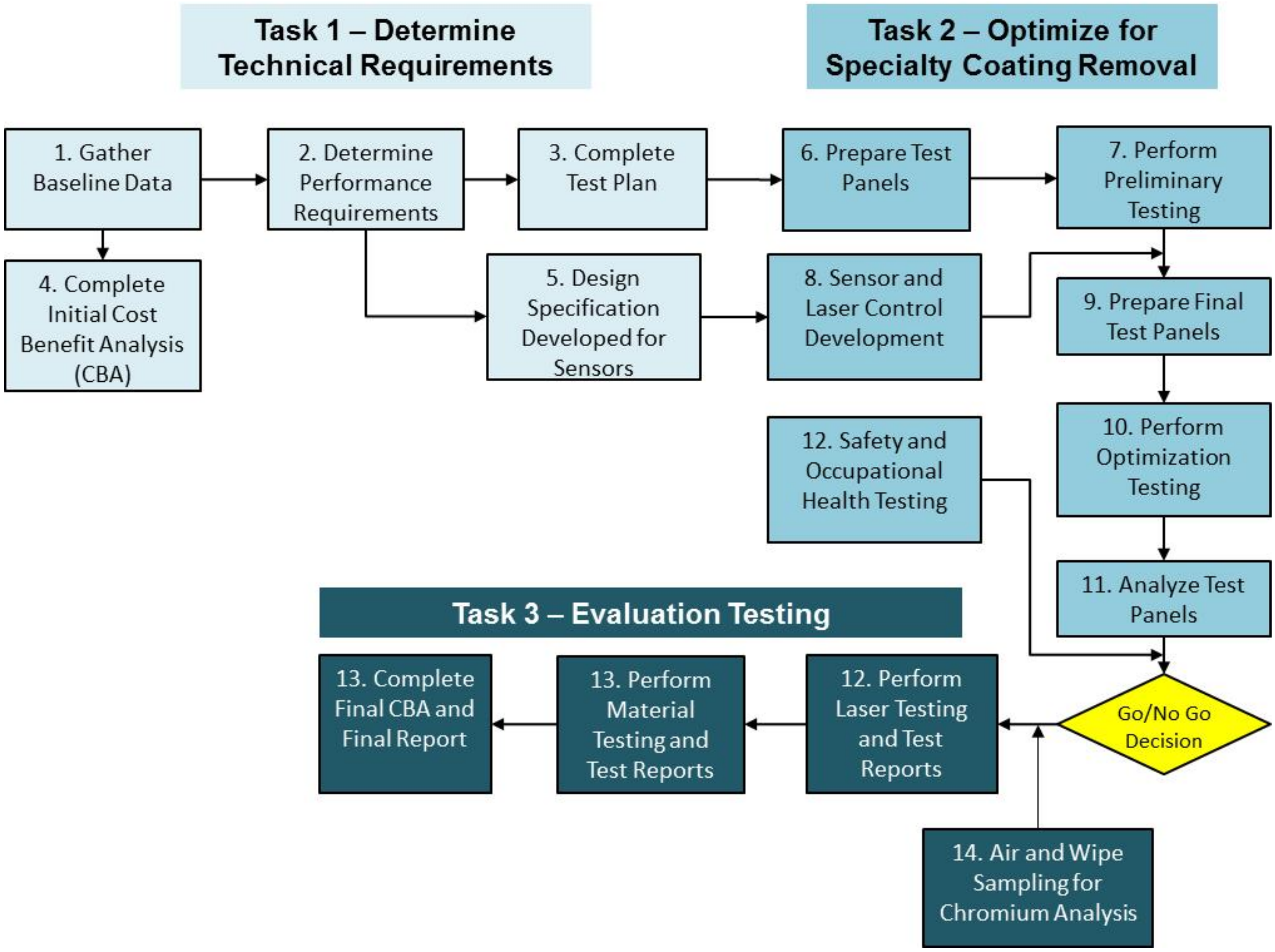

Figure 11. Flow Chart of Technical Activities

3.1 TASK 1 – Determine Technical Requirements

The objective of Task 1 was to determine all the technical requirements for this program, including gathering baseline information, determining the weapon system performance requirements, completing a test plan, completing design specification for the sensors, and completing an initial Cost Benefit Analysis (CBA). These technical activities are described in further detail in the subsections below.

3.1.1 Gather Baseline Information

In support of the development of the initial CBA report outlined in Section 3.1.4, baseline process information for the various weapon system coating removal methods was collected through questionnaires, discussions, and site visits.

3.1.2 Determine Performance Requirements

Prior to the development of any test plan, the system requirements were first identified and discussed with the project team members through email, teleconferences, and face-to-face review meetings. All system requirements were accurately captured at the beginning of the program to ensure that the laser coating removal process developed met the production needs of the weapon systems. The system requirements were collected during the project kick-off meeting in March 2011, as well as internal project team meetings.

The laser removal performance requirements identified included the following laser removal goals and surface temperature requirements:

- Front surface substrate temperature reading ≤ 250 degrees Fahrenheit (°F)
- Complete Removal Goal – All coating layers above base primer
- Partial Removal Goal – All layers above targeted coating layer or partial removal of a specific layer

The performance requirements for the material testing were established by each of the weapon systems and were outlined in the individual Evaluation Test Plans developed for each of the weapon systems.

3.1.3 Developed Test Plans

The project team identified the test procedures, methodologies, and acceptance criteria that were used to evaluate the developed laser coating removal process. Reviews determined that several test plans would be required to accomplish the various testing activities that were identified. Separate test plans were completed for the Preliminary and Optimization Laser Testing, Safety and Occupational Health Testing, and Evaluation Testing for each of the weapon systems evaluated.

3.1.4 Initial Cost Benefit Analysis

As part of this task, an initial CBA was completed, which analyzed the potential financial impact of implementing a robotic laser coating removal system at a depot maintenance type facility to replace the current full aircraft depainting process for the targeted aircraft. The CBA report was based on information gathered on the baseline processes and the information known about the laser coating removal process based on the preliminary laser testing work completed under Task 2 activities (see Section 3.2). This initial CBA preliminarily established that the alternative laser coating removal process is time effective and cost effective over the current coating removal methods.

3.1.5 Design Specifications Developed for Sensors

Based on the performance requirements that were established, the project team completed the design specifications used for the development of the sensors. This design specification included the relevant technical items that the sensors package is required to meet. These items included material compatibility, resolution, repeatability, response time, range, and input/output requirements. The two sensor systems that were developed specifically for the specialty coating removal were the spectral emission sensor system and the coating thickness measurement sensor system which are discussed in further detail in Section 3.2.2.

3.2 TASK 2 – Optimization for Specialty Coating Removal

The objective of Task 2 was to complete preliminary laser testing, develop the sensor technologies and control interfaces, and optimize the laser parameters for complete or selective removal of specialty coatings. Additionally, safety and occupational health activities were performed to include air sampling, wipe sampling, and flammability testing during the laser coating removal process. These technical activities are described in further detail in the subsections below.

3.2.1 Prepare Test Panels

Flat test panels were prepared in various sizes of either 12 inches by 12 inches or 12 inches by 18 inches, and were prepared in two phases. The first phase of panel preparation included the fabrication of the preliminary and sensor optimization test panels. The second phase of the panel preparation included the fabrication of the evaluation test panels which were completed after Evaluation Test Plans were finalized.

The fabrication and coating of the test panels were completed at two different locations based on the weapon system designated for that location. The two locations included the Special Test and Research Laboratory at Wright-Patterson Air Force Base (WPAFB) in Dayton, OH, and Northrop Grumman Corporation in Palmdale, CA.

3.2.2 Preliminary Laser Testing

Preliminary laser coating removal was performed on initial test panels using the 6 kW fiber laser system at CTC in Johnstown, PA. This testing was performed for informational purposes only to establish the feasibility of laser coating removal of specialty materials. This laser testing,

completed at full laser power with no sensor controls, showed that the 6 kW laser system could remove all of the project's targeted coating systems.

3.2.3 Sensor and Laser Control Development

Due to the unique coating removal goals associated with specialty coatings, sensor technologies were integrated into the fiber laser system at CTC ETF and evaluated for use in the laser system's control programming. The sensor feedback is used to control the application of the laser in the coating removal process to enable partial and selective stripping capabilities. The two sensor technologies modified for specialty coating removal applications and tested under this program were a thickness sensor for partial coating removal applications and a surface emissions monitor (SEM) sensor for selective coating removal applications.

The coating thickness sensor, manufactured by Picometrix LLC, was mounted on the end effector fixture, below and aside of the laser scanner, as shown in Figure 12. The thickness measurement sensor technology is a non-contact time-domain terahertz based system that uses a pulsed electro-magnetic signal for sample measurement.

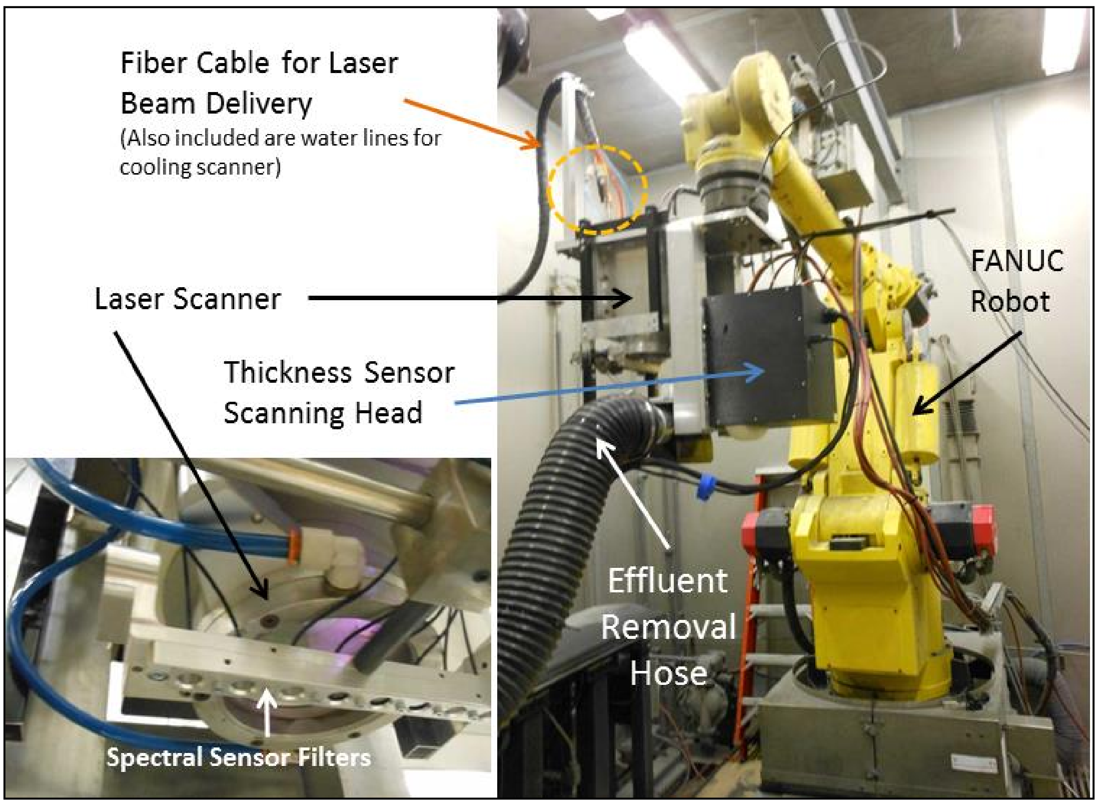

Figure 12. Sensors Integrated into Fiber Laser System at CTC ETF

As shown in Figure 13, the system measures the delta time-of-flight between reflection peaks from front and rear surfaces of coating. The delta time value, measured in picoseconds, is directly correlated to coating thickness. This thickness information is then sent to the laser

process control software which controls the laser power in real-time to enable partial removal of the coating layer and allow a selected thickness to remain.

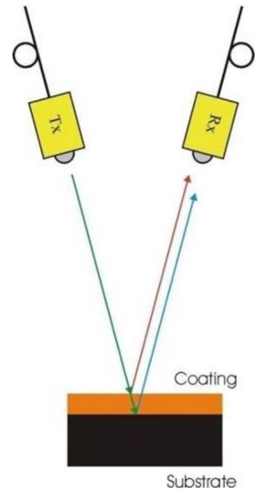

Figure 13. Thickness Sensor System Time-of-Flight Measurement

The SEM sensors are mounted directly below the laser scanner (refer to Figure 9) in order to detect the reflected light from the laser coating removal process. This system uses four sensors during the laser ablation process to detect various spectral ranges of visible and infrared emissions. The emissions are converted to an electrical signal proportional to the intensity of certain wavelengths. Optical filtering techniques are applied to further enhance the selectivity of the sensor. The electrical signals are sent to the laser process control software, and then, based on the thresholds established, used to control laser output power in real-time to allow removal of only the targeted coating areas. In short, this enables the selective stripping of top coating layers, while protecting the underlying coating layers and substrate. In order to effectively remove one coating while leaving the other coating intact, the emission values from the different coatings must not overlap. If they do overlap, the result would be either imparting too much laser energy into the coating that must remain intact and thus potentially damaging the coating, or leaving too much of the coating selected to be removed and thus failing to selectively remove the coating.

3.2.4 Sensor Optimization Testing

Thermocouple Panel Testing

In order to facilitate sensor optimization testing, three test panels were prepared for thermocouple potting by machining 4 recesses into the back of each as shown is Figure 14. The recesses were machined on a Bridgeport mill to a depth of 0.100″ ± 0.001″. Each recess was measured with a calibrated Starret depth micrometer and was thoroughly cleaned with isopropyl alcohol before potting.

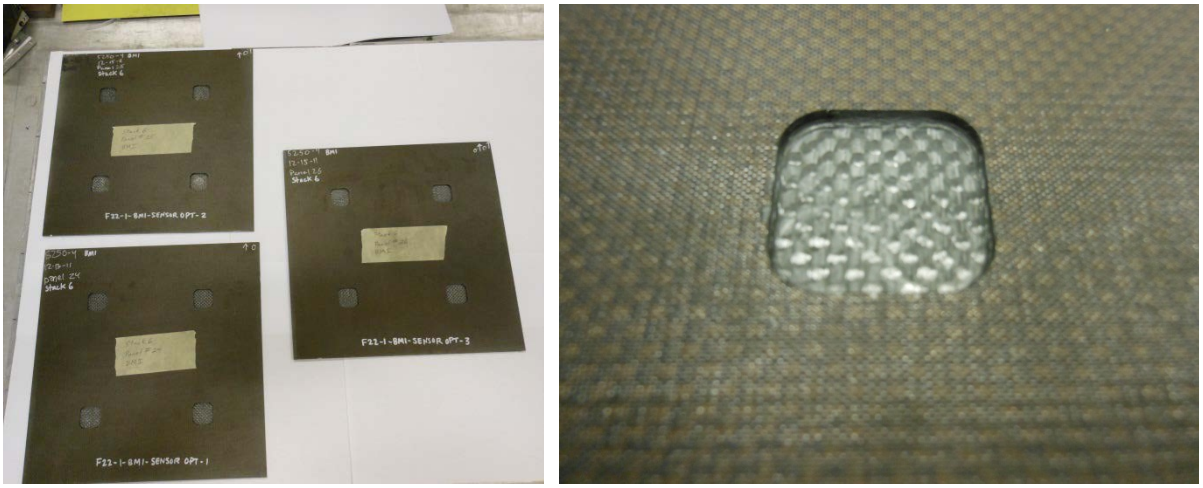

Figure 14. Panel Recesses

Omega type K thermocouples (part# SA1-K-SC) were ordered for this task as shown in Figure 15. The adhesive pad was removed from the thermocouple junction to increase temperature sensitivity.

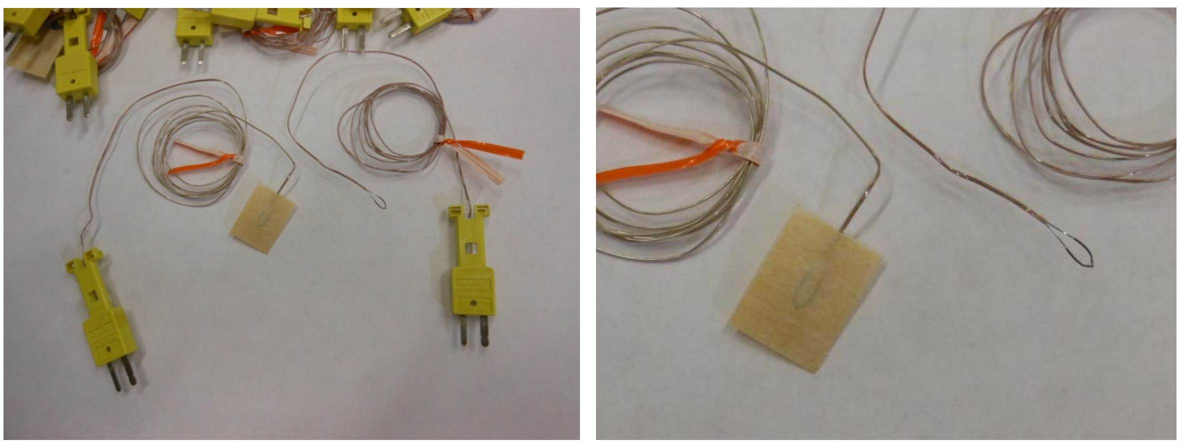

Figure 15. Thermocouples

The thermocouple was bent slightly to ensure that the tip was in direct contact with the bottom of the recess. The lead wire is held in place with masking tape as shown in Figure 16.

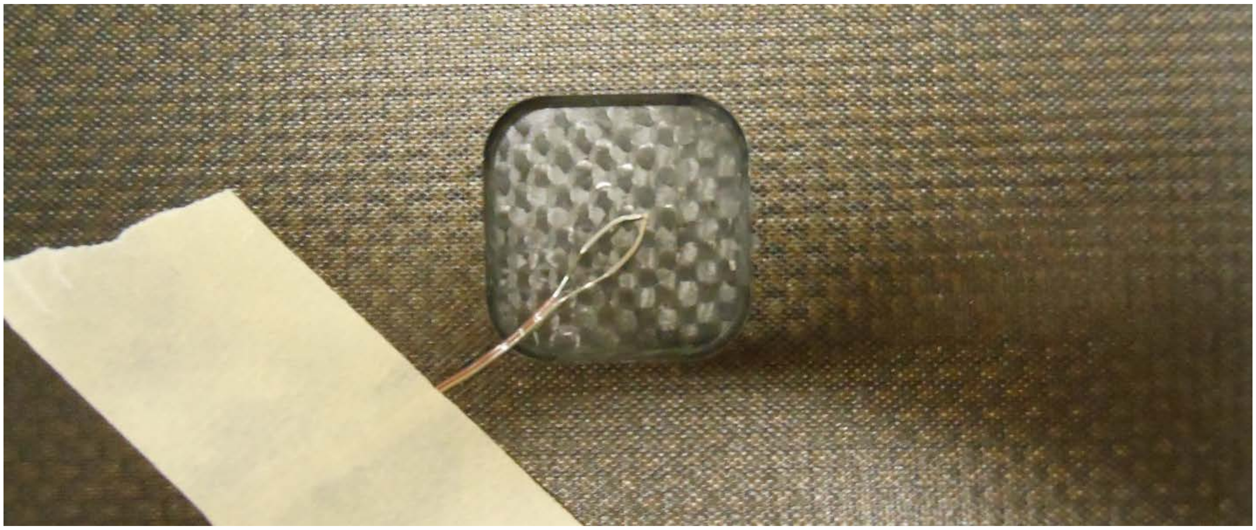

Figure 16. Thermocouple Placement

The recesses were filled with 3M Scotch Weld DP 270 clear potting compound, which was the potting compound recommended by AFRL (see Figures 17 and 18).

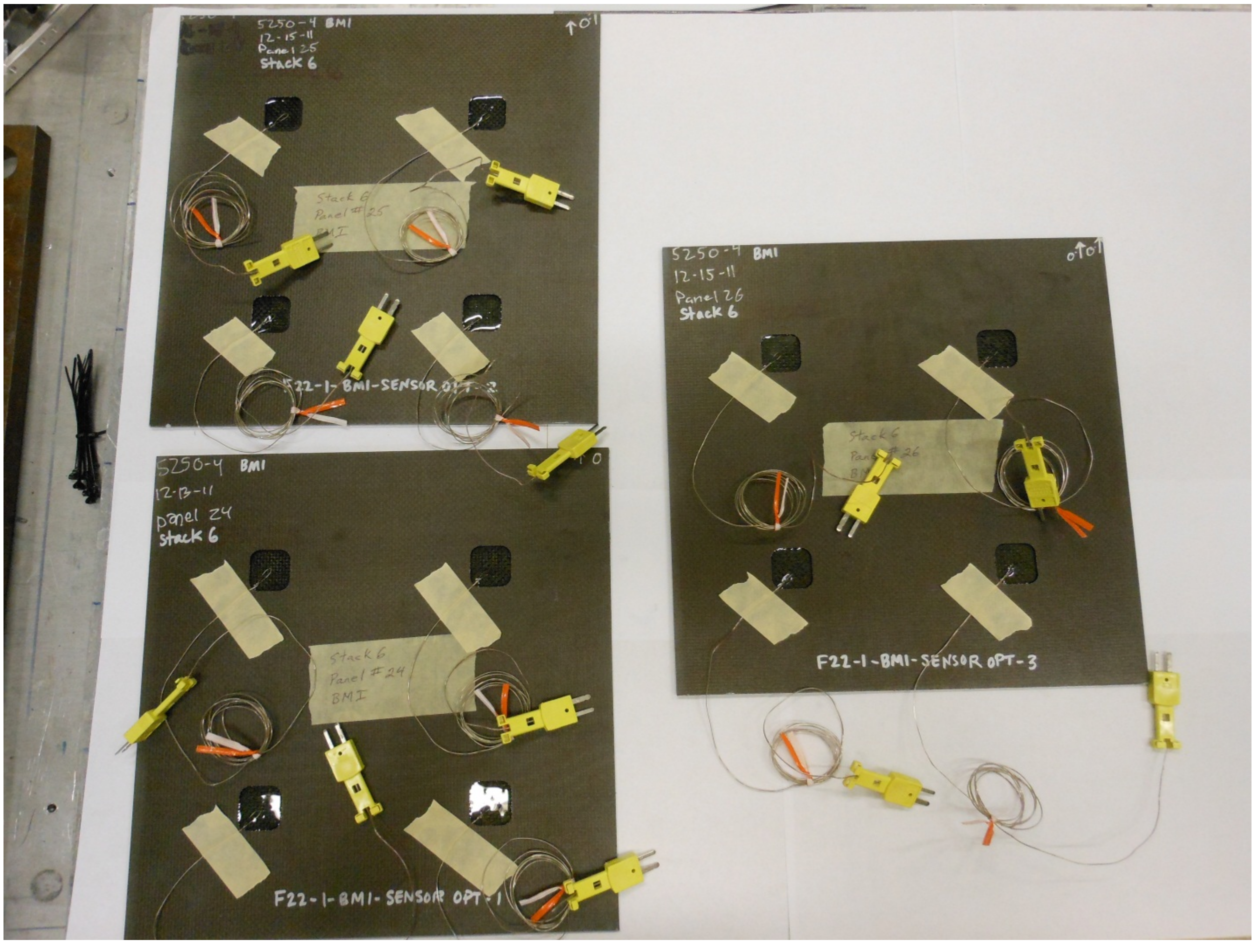

Figure 17. Potting Compound Installation

Figure 18. Cured Potting Compound

The potting compound was allowed to cure for a minimum of 48 hours before laser ablation testing.

Tested eight (8) different thermocouple data acquisition rates to determine which rate would provide sufficient temperature data at the lowest acquisition rate. We used a total of three (3) panels as outlined in Table 1 below, and performed 4 tests scenarios per panel. One "test" scenario is defined as one laser pass at full laser power (6 kW) at a given thermocouple reading rate.

Table 1. Test Panels

CTC Panel ID	AFRL Panel ID	Stack-Up
BMI-SENSOR OPT-1	5250-4 BMI, 12-13-11, Stack 6, Panel 24	Full OML stack-up (primer/conduct./primer/topcoat)
-BMI-SENSOR OPT-2	5250-4 BMI, 12-15-11, Stack 6, Panel 25	Full OML stack-up (primer/conduct./primer/topcoat)
-BMI-SENSOR OPT-3	5250-4 BMI, 12-15-11, Stack 6, Panel 26	Full OML stack-up (primer/conduct./primer/topcoat)

Table 2. Test Results

Data Rate	Max Temp (°F)
2 Hz	104.23
50 Hz	111.82
100 Hz	113.23
1,000 Hz	108.11
5,000 Hz	114.90
10,000 Hz	111.09
15,000 Hz	107.71
20,000 Hz	111.97
50,000 Hz	Computer data max - error
100,000 Hz	Not tried

Small variances were seen in max temperatures between the different acquisition rates (Table 2). Possible reasons are:

- Coating thickness variance across panels
- Thermocouple placement difference – all thermocouple head were placed to touch the bottom of the routed out area, but there is still variance between test areas on how much of the thermocouple head is touching the substrate.
- Thermocouple wire accuracy is +/- 4°F (+/- 2.5 °C).

Sample test panel after laser ablation is shown in Figure 19.

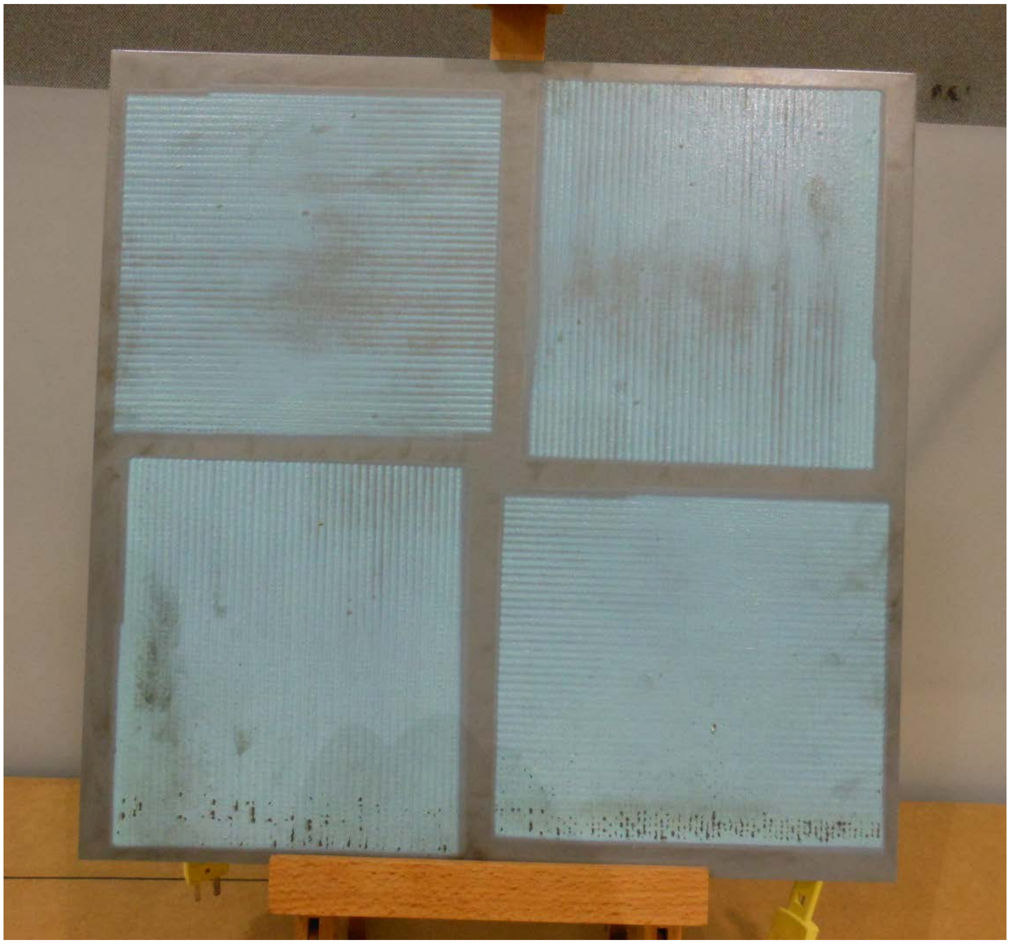

Figure 19. Sample Stripped Panel

Spectral Sensor Optimization

Introduction: During laser ablation of aircraft coatings, portions of the electro-magnetic (EM) spectrum are emitted and/or reflected. The amount of emitted/reflected energy is proportional to the amount of laser energy induced. A broad band, fiber optic spectrometer may be used to measure and record the ultraviolet, visible, and infrared portions of the EM spectrum during laser ablation. The discrete differences between the light produced by the various coatings during

ablation can then be leveraged in logical functions of a laser power control system, used to prevent damage or removal of particular elements in a given coating stack-up.

Testing Purpose: The purpose of this testing was to utilize an Avantes AvaSpec-USB2 spectrometer to identify what discrete differences in light spectrums may exist during laser ablation, within coating stack-ups of interest to this project. A 6 kilowatt (kW) iPG fiber laser, operating at 1070 nanometers (nm) was used as the ablation laser during this testing.

Testing Goals: The following are goals were accomplished for each coating within a weapon system stack-up:

1. Measure and record the emitted/reflected energy at different laser power levels
    a. Tested laser power levels include 9, 50, 75, and 100% output. For the 6kW iPG laser, 9% is 540 Watts (W), 50% is 3000W, 75% is 4500W, and 100% is 6000W.
2. Analyze recorded data to determine if differences in coatings are significant enough to be of use in a laser control system

Testing Activities: For this testing, the FANUC robot was programmed to ablate a 5.5-inch wide by 1-inch long path on the test samples. This operation will conserve test material, allowing multiple tests to be performed on each sample. A digital output from the robot operates a control relay just before ablation begins. This relay, in turn, is used to trigger the spectrometer to start taking measurements. For each test, 4 complete spectrometer scans (1 scan per power level), per weapon system, per coating layer were recorded and saved automatically. The 4 scans were compiled in a single graph and saved as a rich text file (.rtf) for reporting. Figure 20 shows the sensor location on robotic laser system. The panels in Table 3 were tested and analyzed.

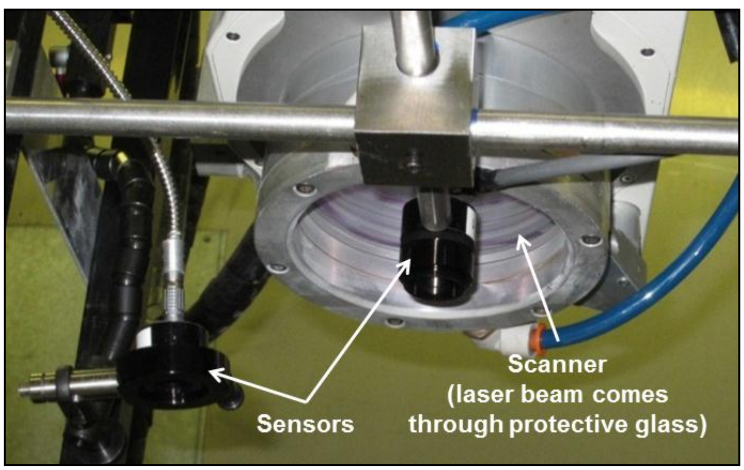

Figure 20. Spectral Sensor Location on Laser System

Table 3. Spectrometer Test Panels

System	Panel ID	Coating Description
A	-SENSOR CAL-1	Primer
	-SENSOR CAL-2	Primer + Conductive
	-SENSOR CAL-3	Primer + Cond. + Primer

System	Panel ID	Coating Description
	-SENSOR CAL-4	Primer + Cond. + Primer + coating
	-SENSOR CAL-5	Primer + Cond. + Primer + coating + Primer
	-SENSOR CAL-6	Primer + Cond. + Primer + coating + Primer + Topcoat
	-SENSOR CAL-4	Primer + Cond. + Primer + Topcoat
B	-SENSOR CAL-1	Primer
	-SENSOR CAL-2	Primer + Topcoat
C	-SENSOR CAL-1	Bare Substrate + Primer (50%)
	-SENSOR CAL-2	Primer + Conductive + Primer (50%)
	-SENSOR CAL-3	Primer + Cond. + Primer + Topcoat
	-SENSOR CAL-3	Primer + Cond. + Adhesive + coating (50%)
	-SENSOR CAL-4	Primer + Cond. + coating + Flex Primer + Topcoat (50%)
	F22-2-SENSOR CAL-5	Primer + Cond. + Adhesive/Boot + Flex Primer + Topcoat
D	A-1B-TG-ST-SENSOR CAL-1	Substrate + Primer (50%)
	A-1B-TG-ST-SENSOR CAL-2	Primer + coating + Primer (50%)
	A-1B-TG-ST-SENSOR CAL-3	Primer + coating + Primer + CARC (Tan 50%, Green 50%)
	A-1B-TG-AL-SENSOR CAL-1	Substrate + Primer (50%)
	A-1B-TG-AL-SENSOR CAL-2	Primer + coating + Primer (50%)
	A-1B-TG-AL-SENSOR CAL-3	Primer + coating + Primer + CARC (Tan 50%, Green 50%)
	A-1B-TG-SG-SENSOR CAL-1	Substrate + Primer (50%)
	A-1B-TG-SG-SENSOR CAL-2	Primer + coating + Primer (50%)
	A-1B-TG-SG-SENSOR CAL-3	Primer + specialty coating + Primer + CARC (Tan 50%, Green 50%)
	A-1B-TG-EG-SENSOR CAL-1	Substrate + Primer (50%)
	A-1B-TG-EG-SENSOR CAL-2	Primer + specialty coating + Primer (50%)
	A-1B-TG-EG-SENSOR CAL-3	Primer + coating + Primer + CARC (Tan 50%, Green 50%)
Generic	S-8-3	BMI substrate
	S-9-16	PEEK substrate

Test Results: For each substrate and coating layer, spectral data was recorded at 9%, 50%, 75%, and 100% laser power levels. The evaluation of spectral responses obtained at different power levels is necessary to determine whether enough difference exists between two adjacent layers to allow for the recognition of each. These differences are then exploited by a control system where logical decisions about applied power levels are made. Typically, when the layer to be removed is detected, the laser power is increased to its maximum 100% (6000W). When the underlying layer (to be kept intact) is detected, the laser power is set to its minimum, 9% (540W) to prevent any appreciable removal.

System A: There are two coating removal goals for System A. Goal #1 is partial removal of the topcoat – removing 2-3 mils of the topcoat. Goal #2 is complete removal of the topcoat leaving the base primer intact.

Goal #1 would need to be accomplished by another sensor technology (i.e., thickness sensor) since the spectral response sensors are used to differentiate between materials, not to determine

actual coating thickness. The spectral response may still be utilized as protection against accidental removal of the primer, but thickness sensing devices or established topcoat strip rates must be used to accurately remove small amounts of the topcoat.

Goal #2 was the focus of this spectral data gathering activities. Figures 3 through 6 below show the spectral responses of the Deft 098 primer and topcoat at 540W and 6000W laser power levels.

A comparison of Figures 21 and 22 show that at the minimum power level (540W), a significant difference in signal amplitude exists at 1070nm between the primer and topcoat. A comparison of Figures 23 and 24 shows that, at 6000W, a difference in signal amplitude exists not only at 1070nm, but in the region of 500 to 800nm as well. It is possible that these differences can be used in a control scheme to effectively remove the topcoat, while leaving the Deft 098 primer intact thus meeting Goal #2.

Figure 21. Primer Response at 540W (9% Laser Power)

Figure 22. Topcoat Response at 540W (9% Laser Power)

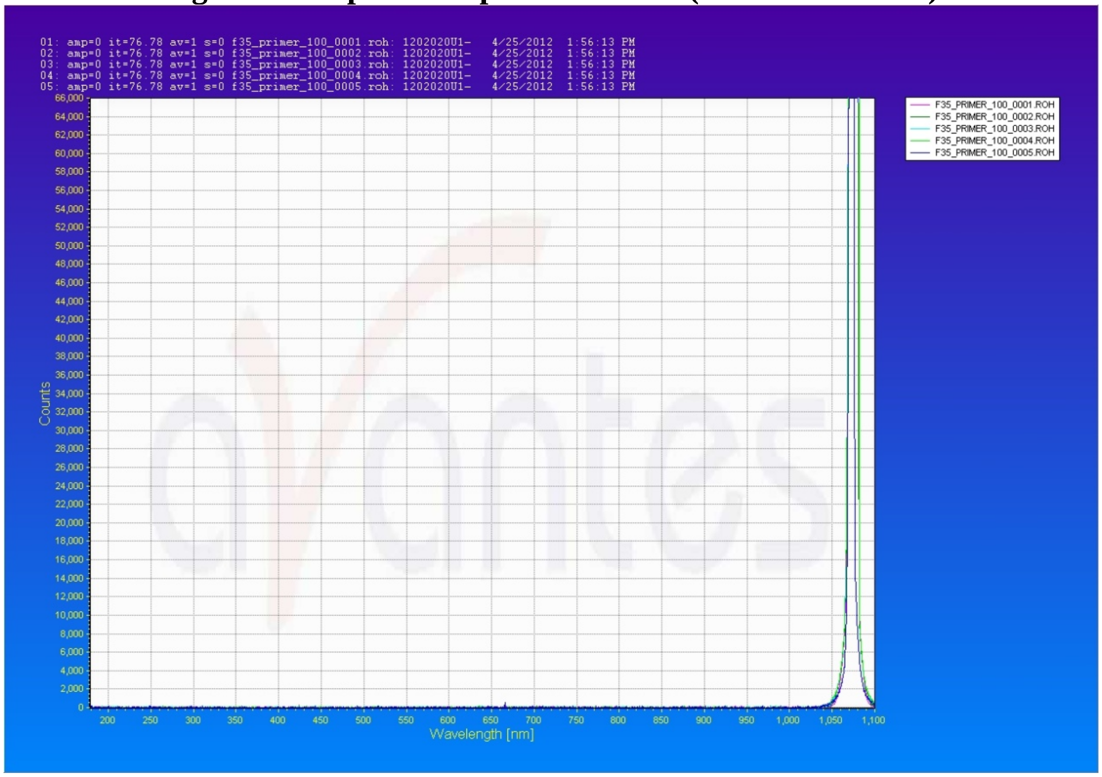

Figure 23. Primer Response at 6000W (100% Laser Power)

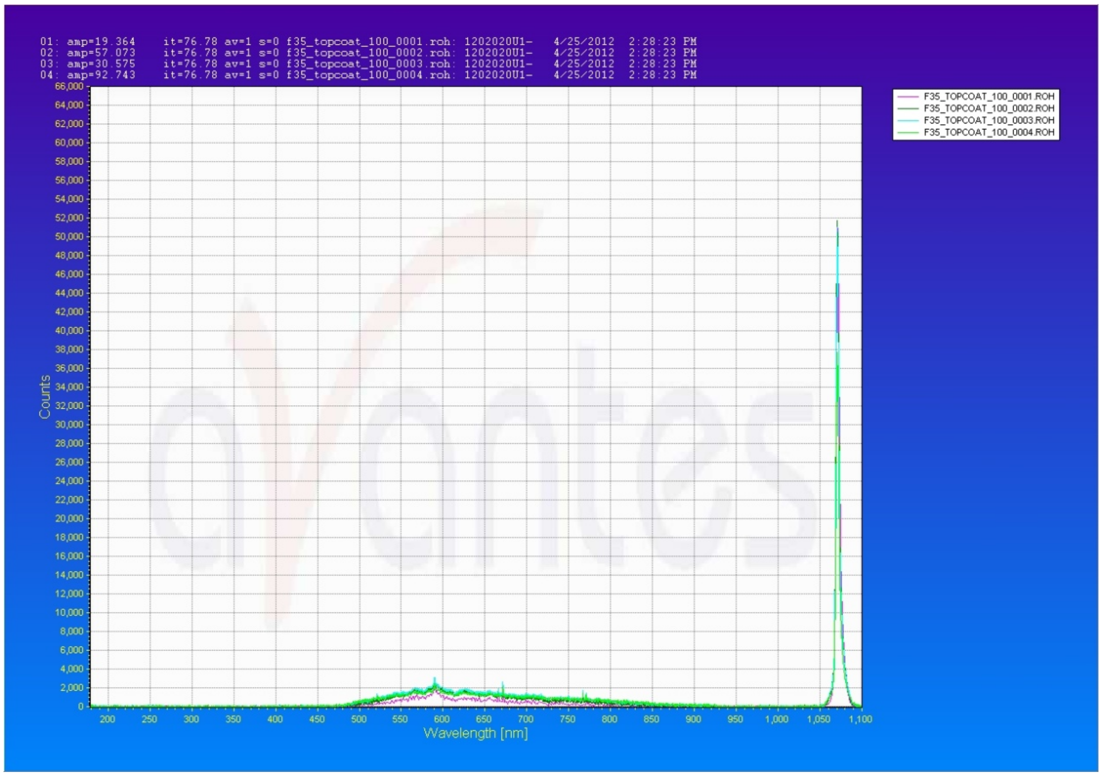

Figure 24. Topcoat Response at 6000W (100% Laser Power)

System A Results Summary: There are differences in signal amplitude at 1070nm at the 540W (9%) and 6000W (100%) laser power levels between the primer and topcoat. As a result, it may be possible that these differences can be used in a control scheme to effectively remove the topcoat, while leaving the primer intact to accomplish the removal Goal #2.

System B Results: There are two coating removal goals for System B. Goal #1 is complete removal of all layers above the base primer. Goal #2 is partial removal – removing the boot material and adhesive and leaving the lower layers.

The focus for Goal #1 is the removal of the conductive layer (and all layers above it) from the primer. Figures 9 through 12 show the spectral responses of the base primer and conductive layers at both 540W (9%) and 6000W (100%) laser power levels.

When comparing Figures 25-28, it is easy to see that there is no appreciable difference in spectral response between the base primer and conductive layers at either power level. It is unlikely that spectral sensors will be useful in accomplishing the goal of removing all layers down to the base primer (Goal #1).

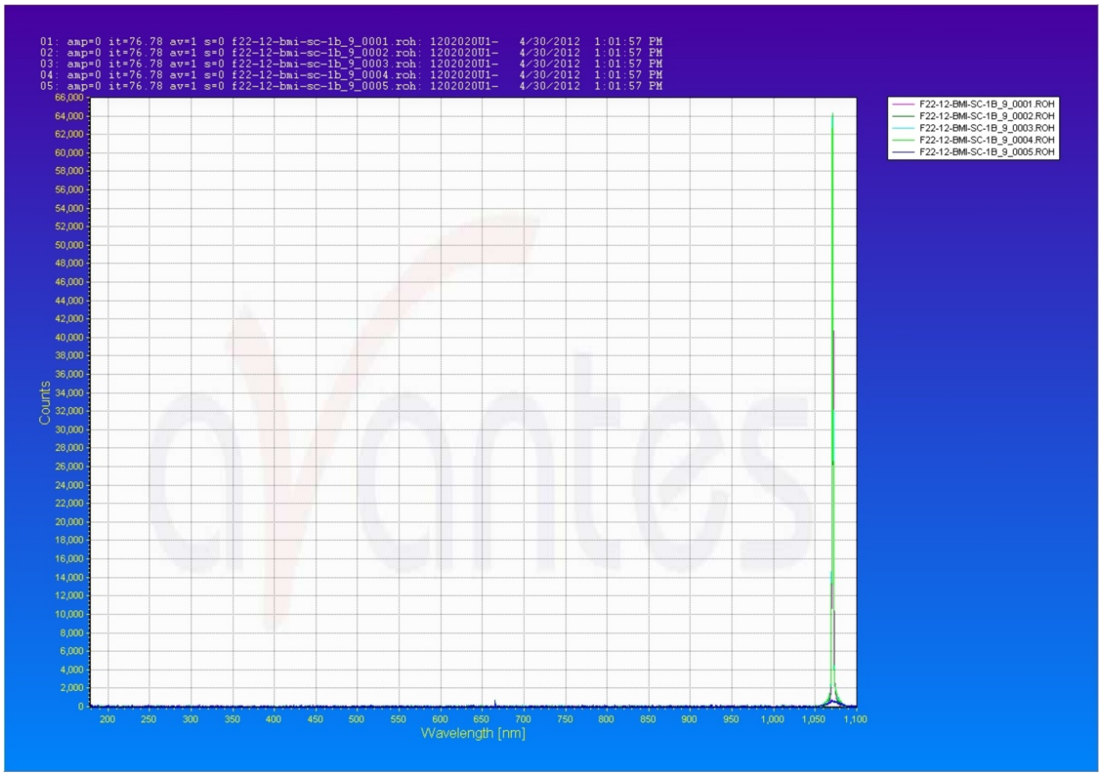

Figure 25. Base Primer Response at 540W (9% Laser Power)

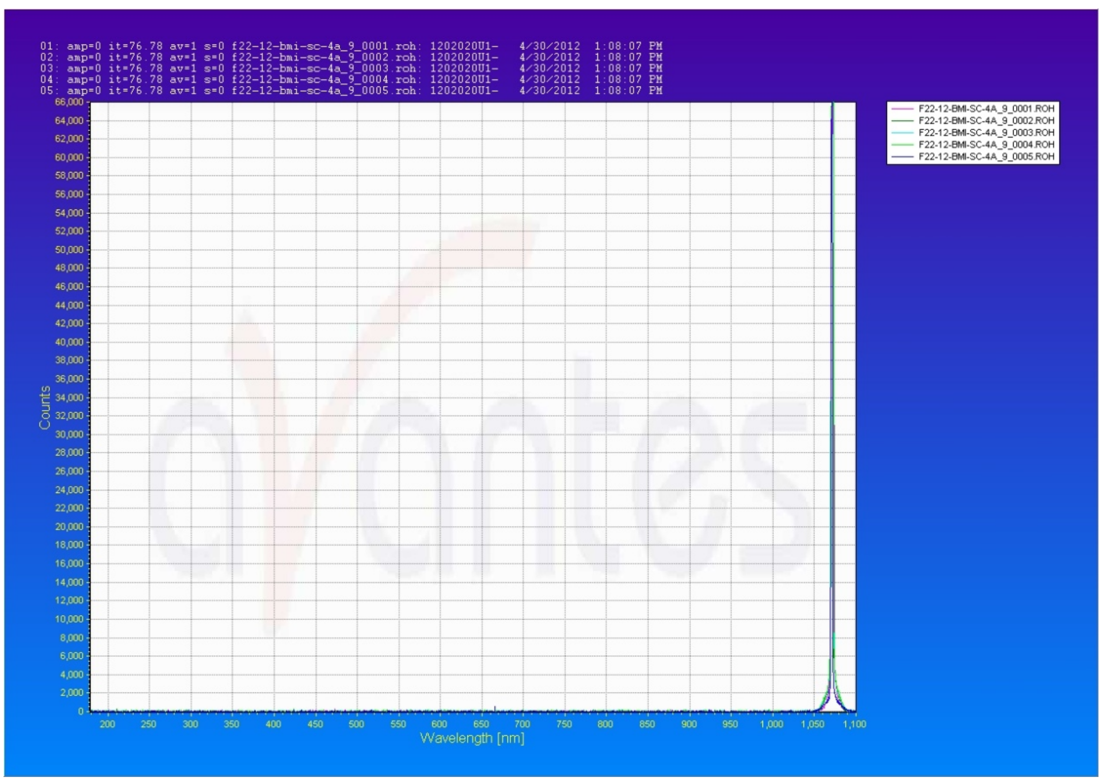

Figure 26. Conductive Layer Response at 540W (9% Laser Power)

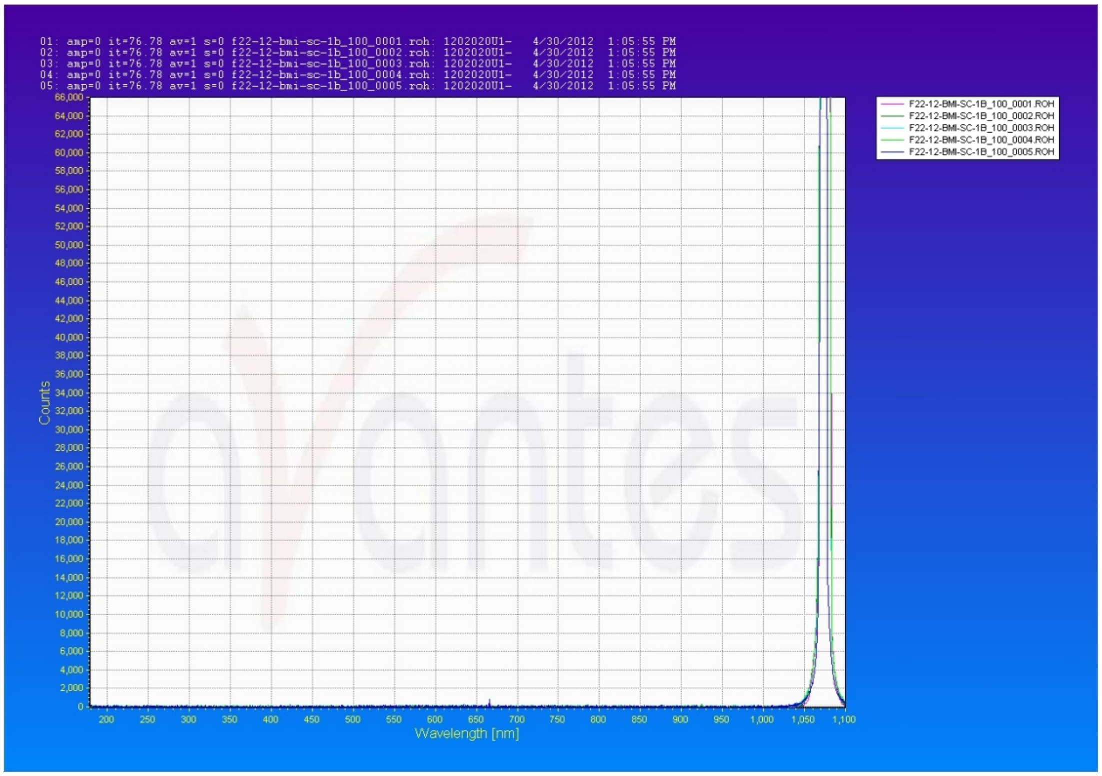

Figure 27. Base Primer Response at 6000W (100% Laser Power)

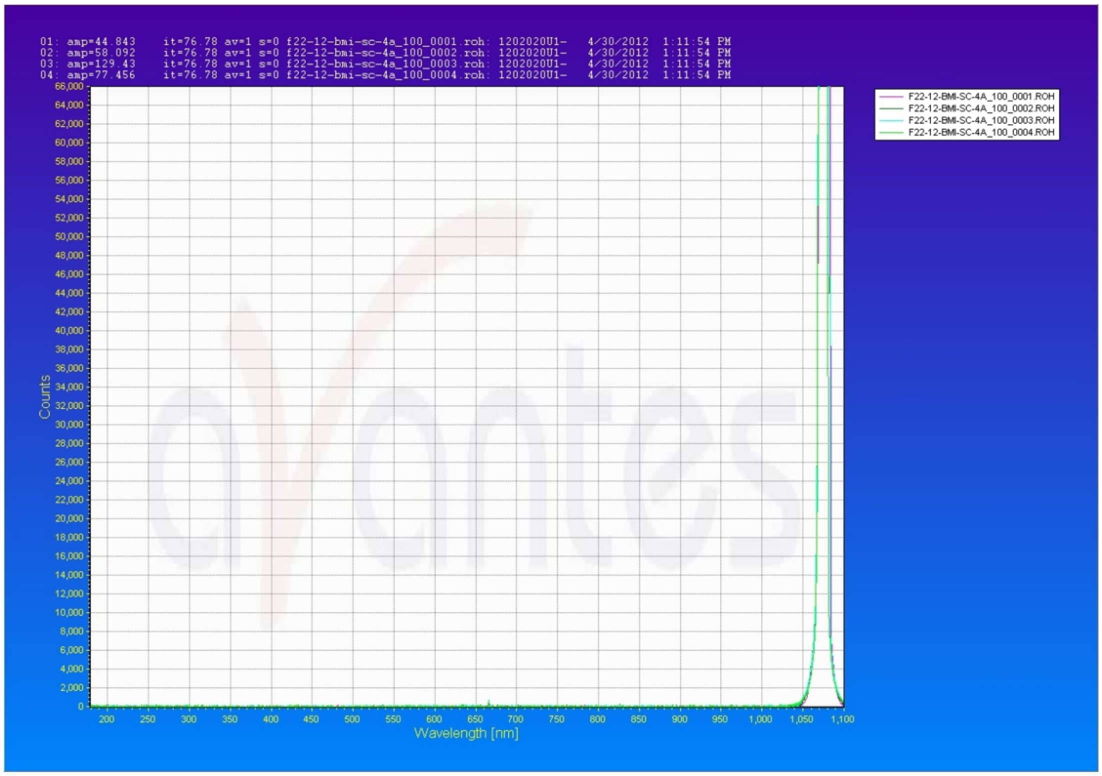

Figure 28. Conductive Layer Response at 6000W (100% Laser Power)

In order to accomplish Goal #2, a difference in spectral response must be seen between the PR-1829 Adhesive and the intermediate primer layer. Figures 29 through 32 document the spectral responses of these coatings at laser power levels of 540W (9%) and 6000W (100%).

Figure 29. Intermediate Primer Response at 540W (9% Laser Power)

Figure 30. Adhesive Layer Response at 540W (9% Laser Power)

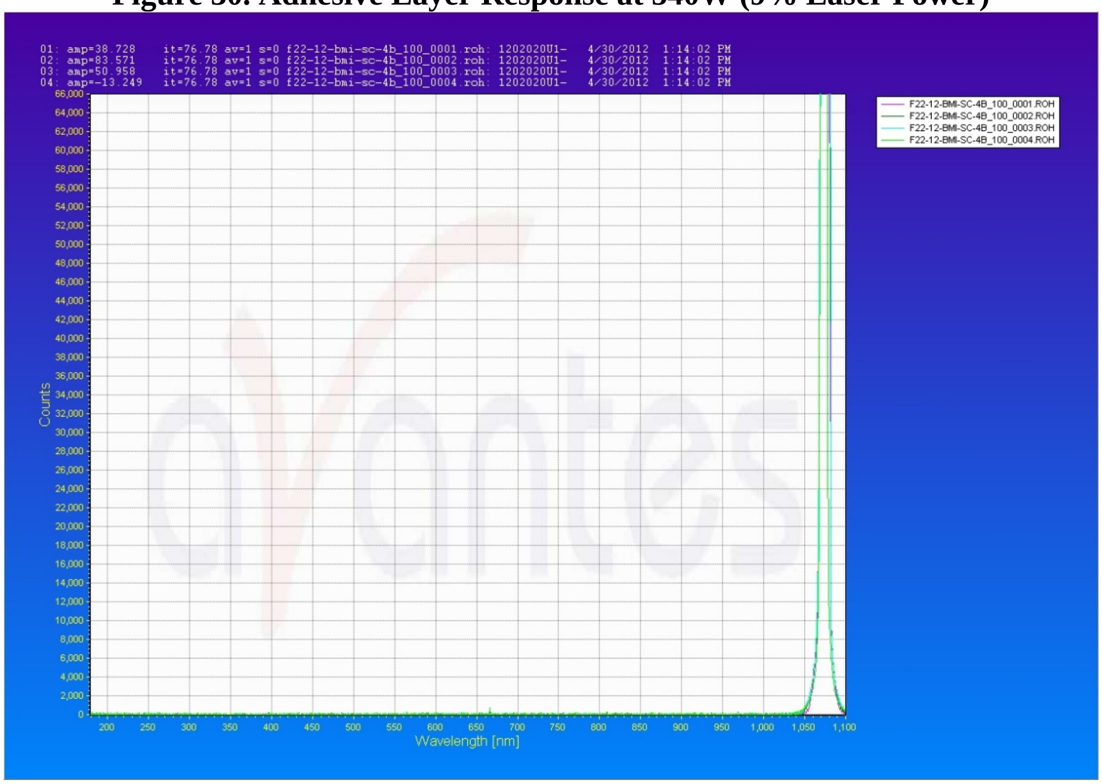

Figure 31. Intermediate Primer Response at 6000W (100% Laser Power)

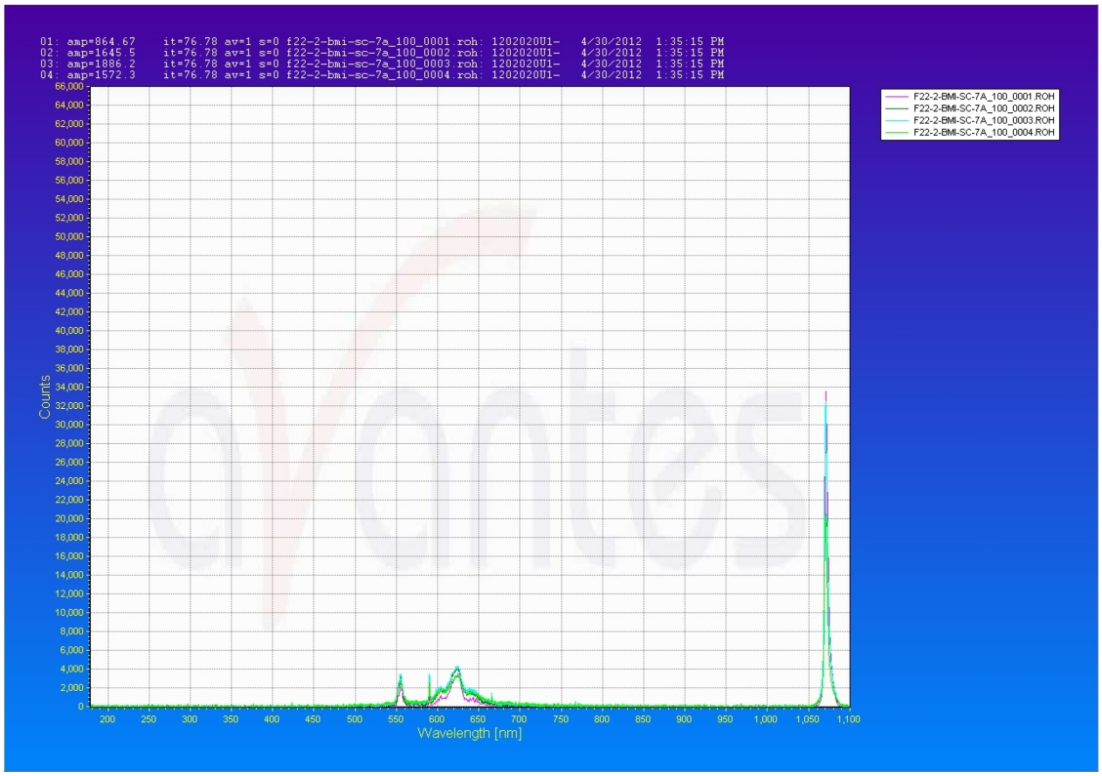

Figure 32. Adhesive Layer Response at 6000W (100% Laser Power)

While there is a noticeable difference in the spectral responses at 6000W (100%), there is not enough of a variation at 540W (9%) to accomplish Goal #2. If a control system cannot recognize the coating of interest, the power level will not be increased to continue ablation of the layer.

System B Results Summary: The spectral data gathered at various laser power levels shows that it is unlikely that spectral sensors will be useful in accomplishing removal Goal #1 or Goal #2. There is no appreciable difference in spectral response between the coating layers at the different power levels to effectively control the laser for selective coating removal using the spectrial information.

System C Results: There are two coating removal goals for System C. Goal #1a is complete removal of all coating layers above the substrate. However, past laser removal experience has shown that there is no way to protect the substrate unless base primer layer is maintained. Therefore, Goal #1b is recommended – the primer be left on the substrate and remove all coating layers above that base primer. Goal #2 is partial removal – removing 2-3 mils of the coating.

Figures 33 through 36 depict the spectral responses to be evaluated for Goal #1b where coating is laid on the base primer.

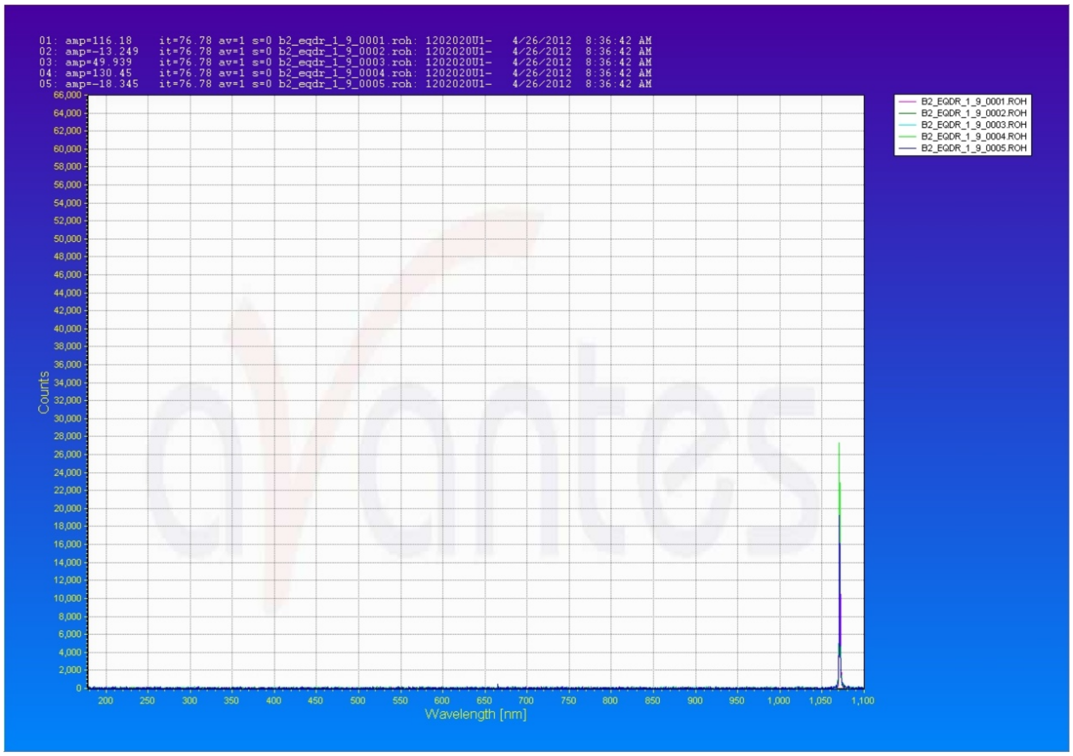

Figure 33. Base Primer Response at 540W (9% Laser Power)

Figure 34. Response at 540W (9% Laser Power)

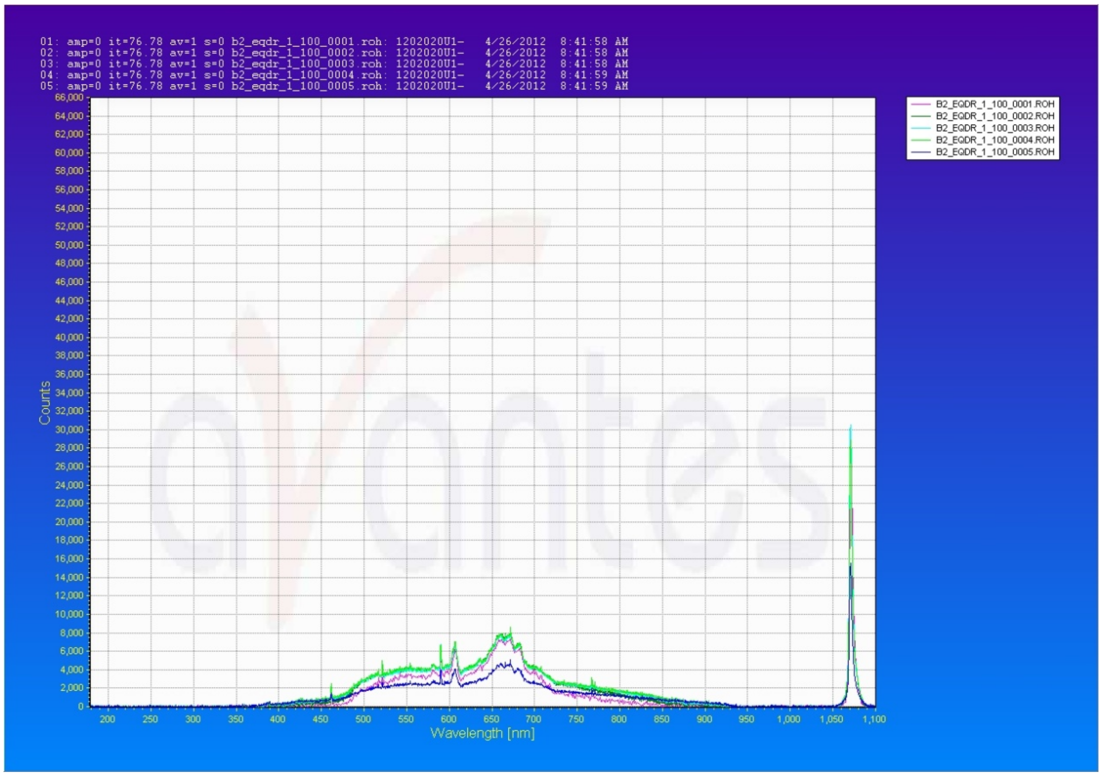

Figure 35. Base Primer Response at 6000W (100% Laser Power)

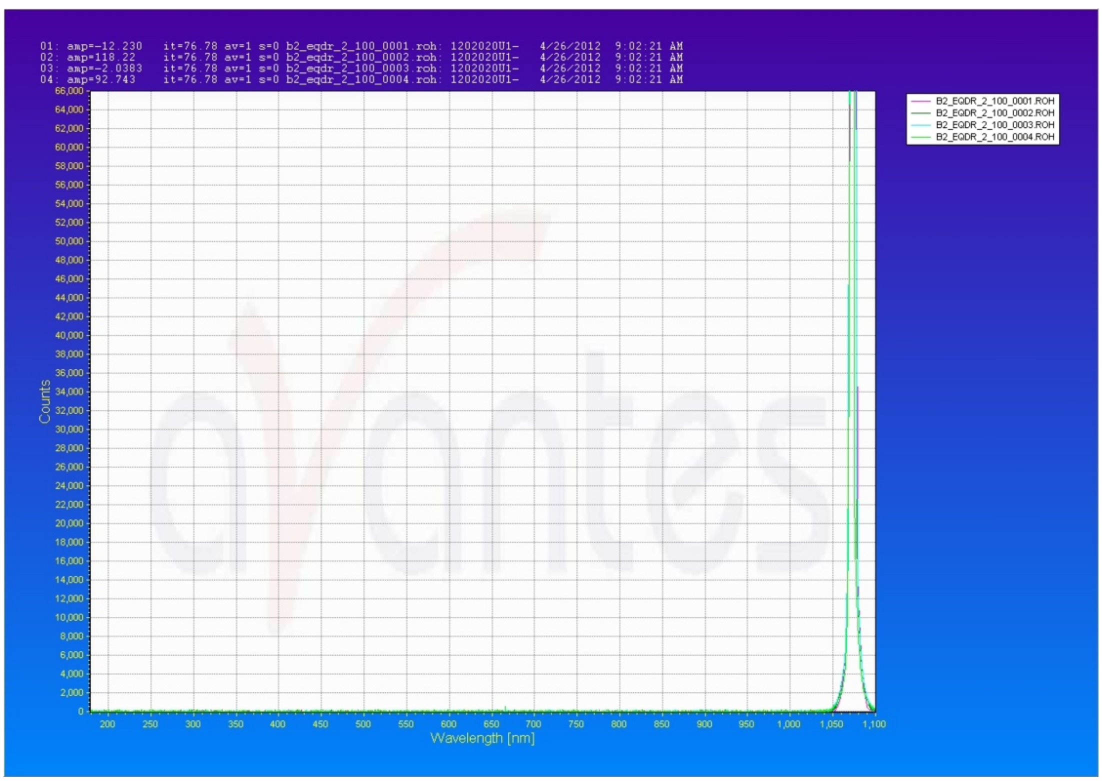

Figure 36. Response at 6000W (100% Laser Power)

As can be seen from the figures above, ample signal differences are present between the two coatings at both the low and high laser power levels. Therefore, it is possible that a spectral sensor system may be used to remove all layers above the base primer.

During spectral response testing, it was noted that the rain erosion stack-up was very sensitive to the fiber laser power and was easily damaged. Since the base primer layer is necessarily thin, it is doubtful that all coating layers could be removed without destroying the film. Therefore, CTC proposes that coatings in this particular stack-up be removed only to the base layer of primer in an attempt to prevent substrate damage (Goal #1b). To this end, Figures 37 through 38 show the spectral responses of the base primer and rain erosion coating at 540W (9% laser power) and 6000W (100% laser power). The Figures 39 and 40 are shown in order to see the comparisons more clearly.

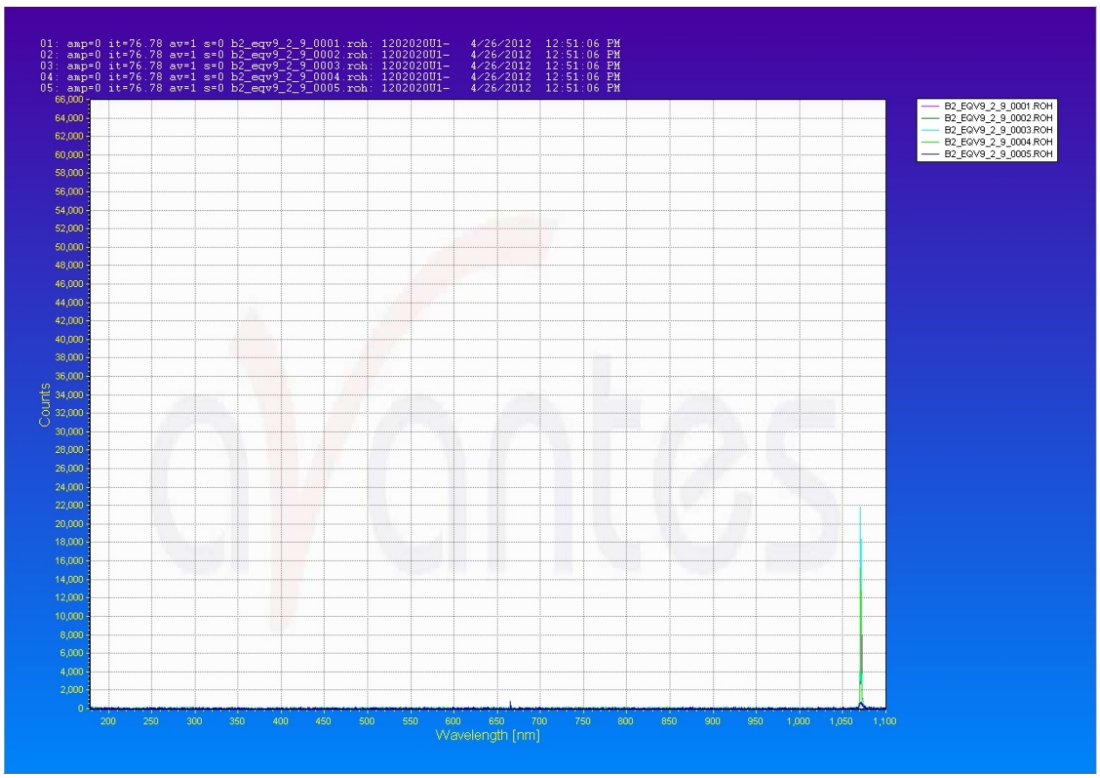

Figure 37. Base Primer Response at 540W (9% Laser Power)

Figure 38. Rain Erosion Coating Response at 540W (9% Laser Power)

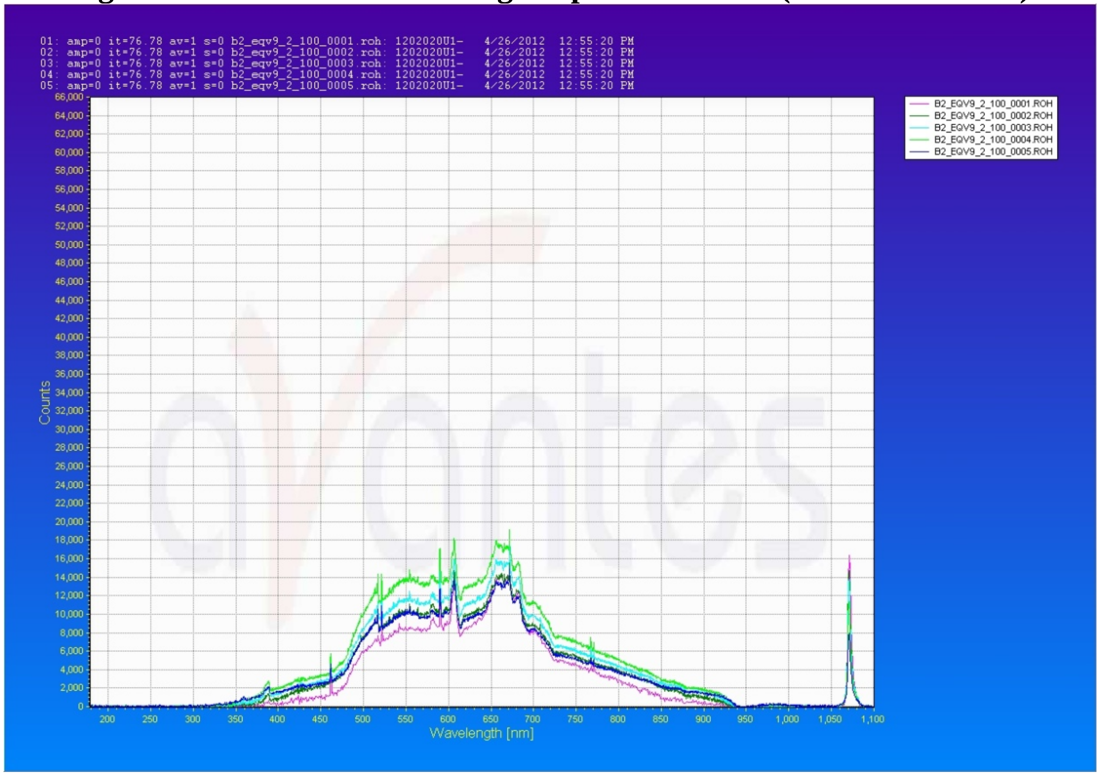

Figure 39. Base Primer Response at 6000W (100% Laser Power)

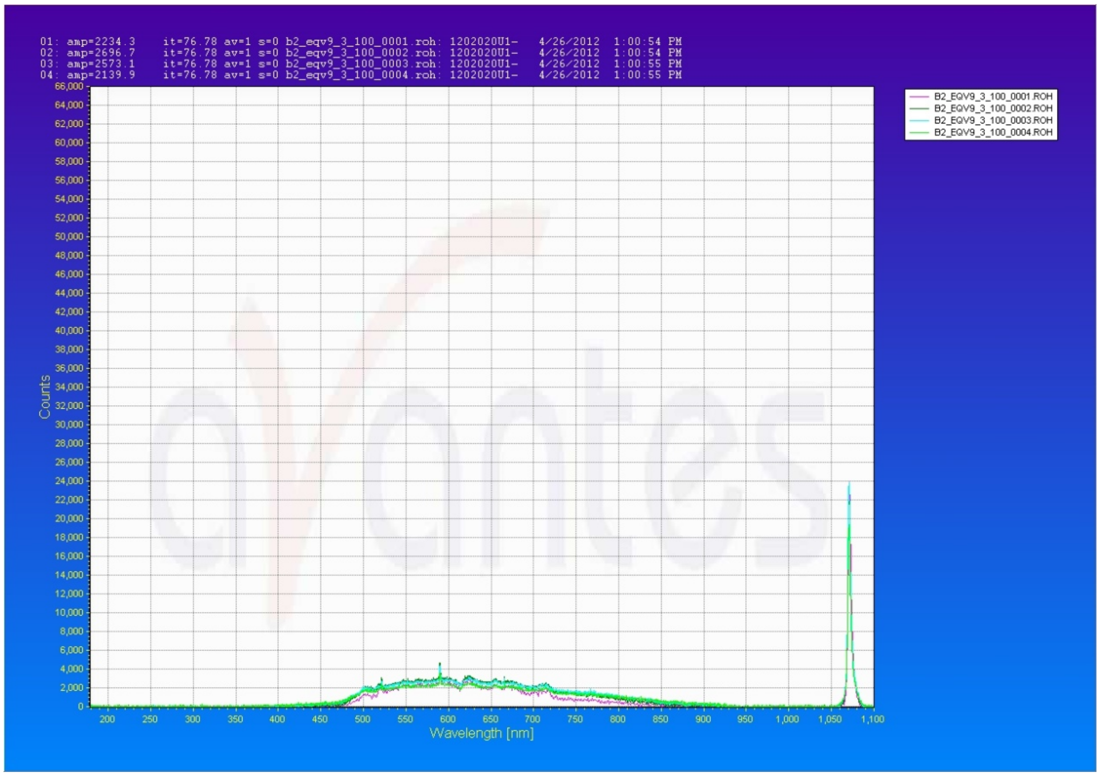

Figure 40. Rain Erosion Coating Response at 6000W (100% Laser Power)

Strong differences do exist between the spectral responses of the base primer and rain erosion coating. Because of this, the chances of removing the coating stack-up and protecting the base primer and fragile coating layer are greatly increased. Further trials are needed to prove this concept.

Goal #2, partial removal of the coating material, will not be met using spectral sensors. As with the System A coating stack-up, thickness sensors or proven coating strip rates are needed to control the removal of 2-3 mils.

System C Results Summary: For complete removal of all coating stack-ups, ample signal differences are present between the base primer and the coating at both the low and high laser power levels. Therefore, it is possible that a spectral sensor system may be used to remove all layers above the base primer.

For complete removal of rain erosion coating, strong differences exist between the spectral responses of the base primer and rain erosion coating at both the low and high laser power levels. Therefore, it is possible that a spectral sensor system may be used to remove all layers above the base primer.

System D: There are three coating removal goals for System D. Goal #1 is complete removal of all coating layers above the base primer as shown in Figure 41. Goal #2 is complete removal of the CARC topcoat layer. Goal #3 is partial removal of the surrogate material – removing 2-3 mils of the surrogate.

The coating stack-up presents a difficult set of challenges for a spectral sensor-based coating removal control system. With the possible exception of the green and tan CARC topcoats at 100% laser power, the spectral responses of all the coatings in the stack-up are nearly identical. Figures 42 through 44 show the responses of the base primer and surrogate coating (in support of Goal #1).

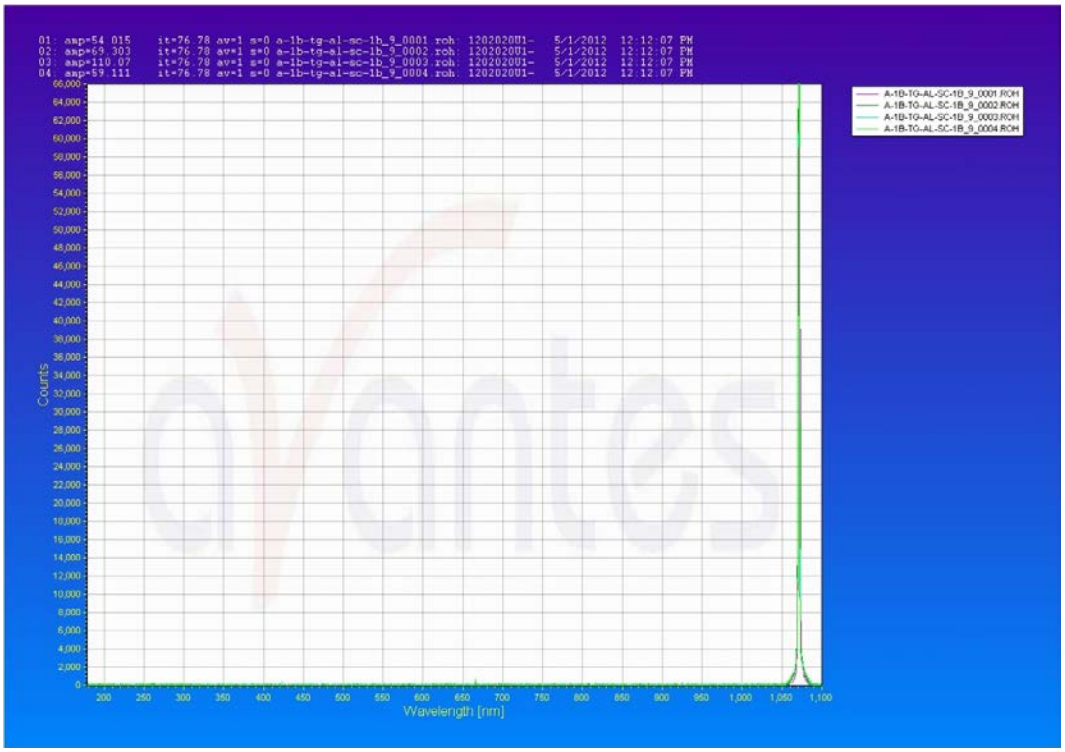

Figure 41. Base Primer Response at 540W (9% Laser Power)

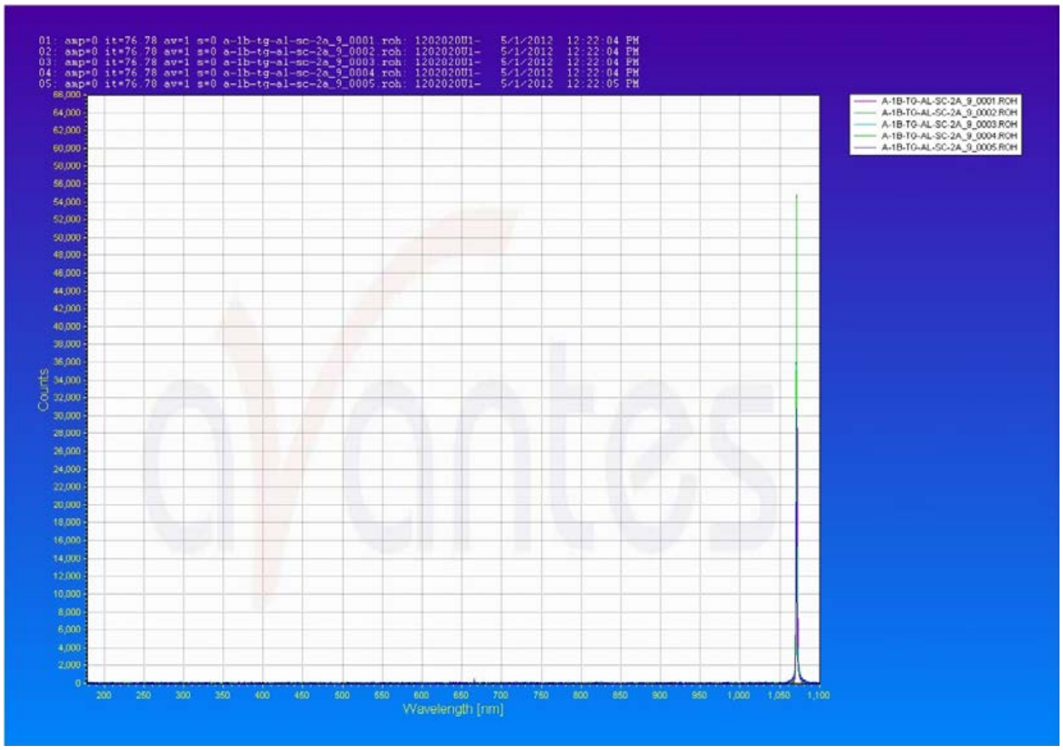

Figure 42. Surrogate Coating Response at 540W (9% Laser Power)

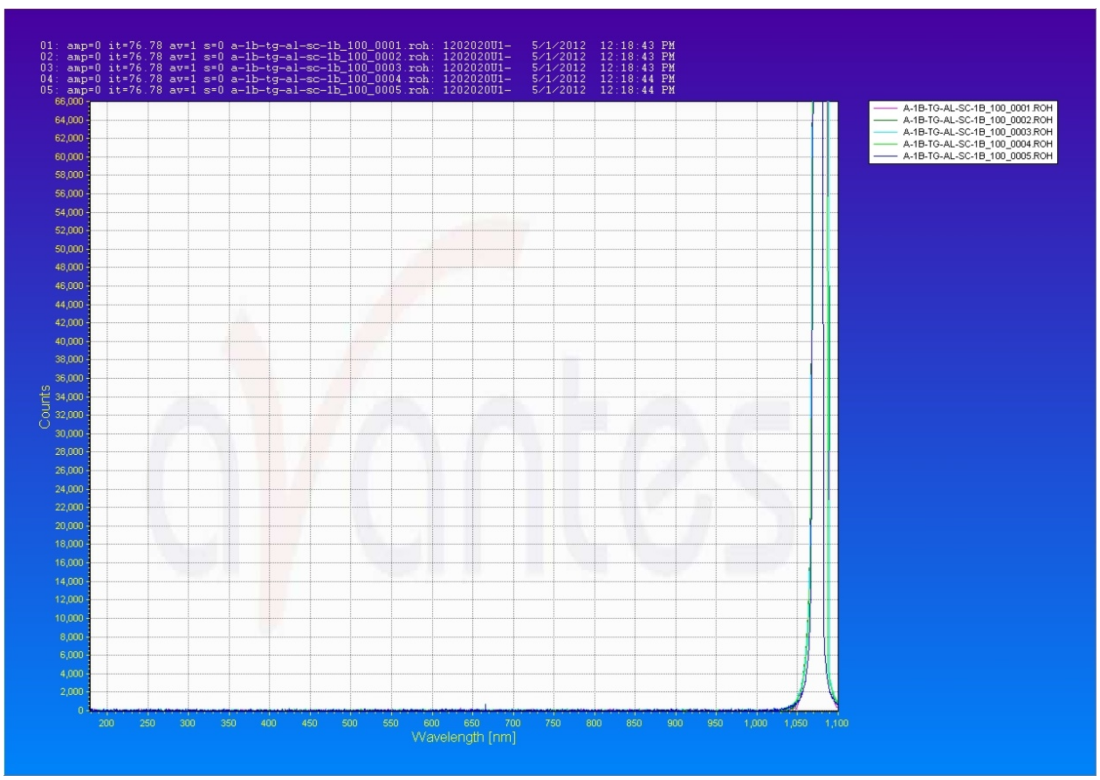

Figure 43. Base Primer Response at 6000W (100% Laser Power)

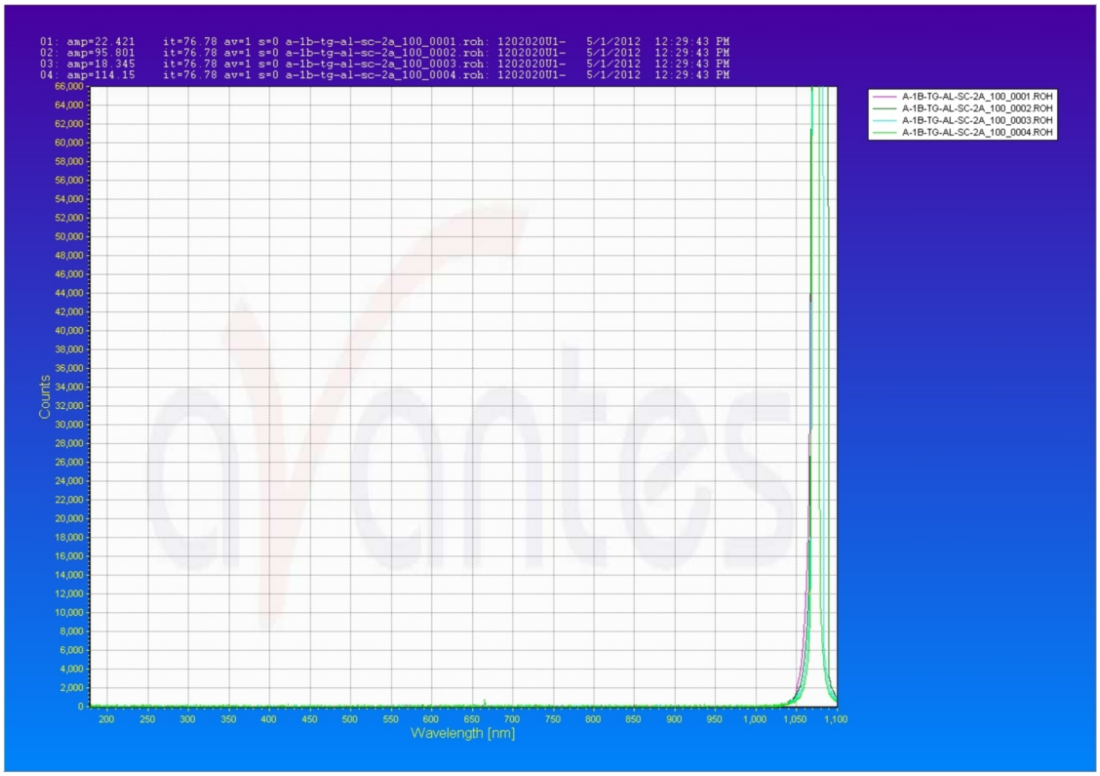

Figure 44. Surrogate Coating Response at 6000W (100% Laser Power)

Aside from a small amplitude difference at 540W, there is little difference between the primer and surrogate coating that can be detected. Therefore, using a spectral sensor to effectively control removal of all materials down to the base primer (Goal #1) is extremely unlikely.

Figures 45 through 48 show the responses of the Upper Primer and Tan CARC coatings (sensory results in support of Goal #2).

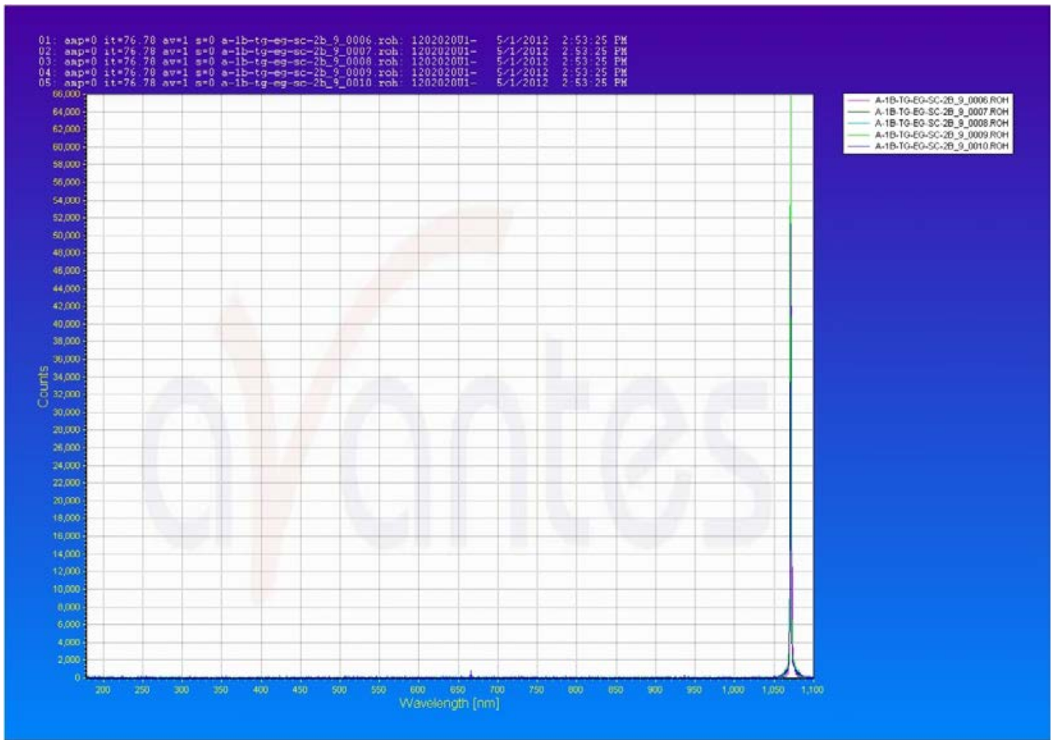

Figure 45. Upper Primer Layer Response at 540W (9% Laser Power)

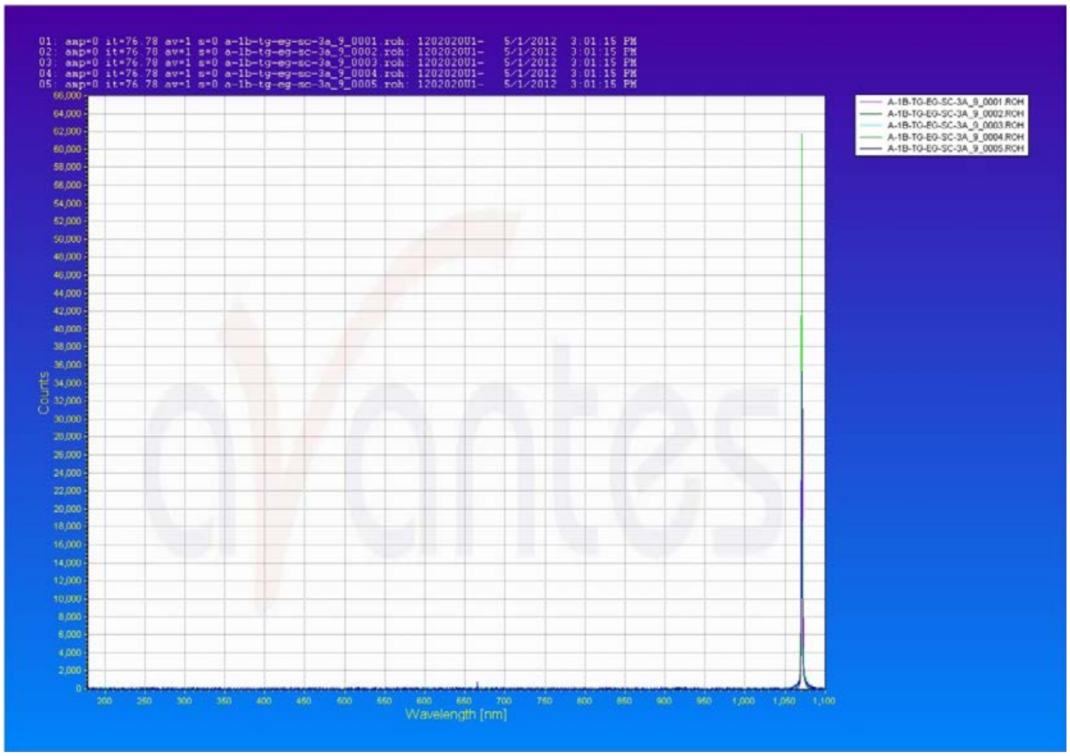

Figure 46. Tan CARC Response at 540W (9% Laser Power)

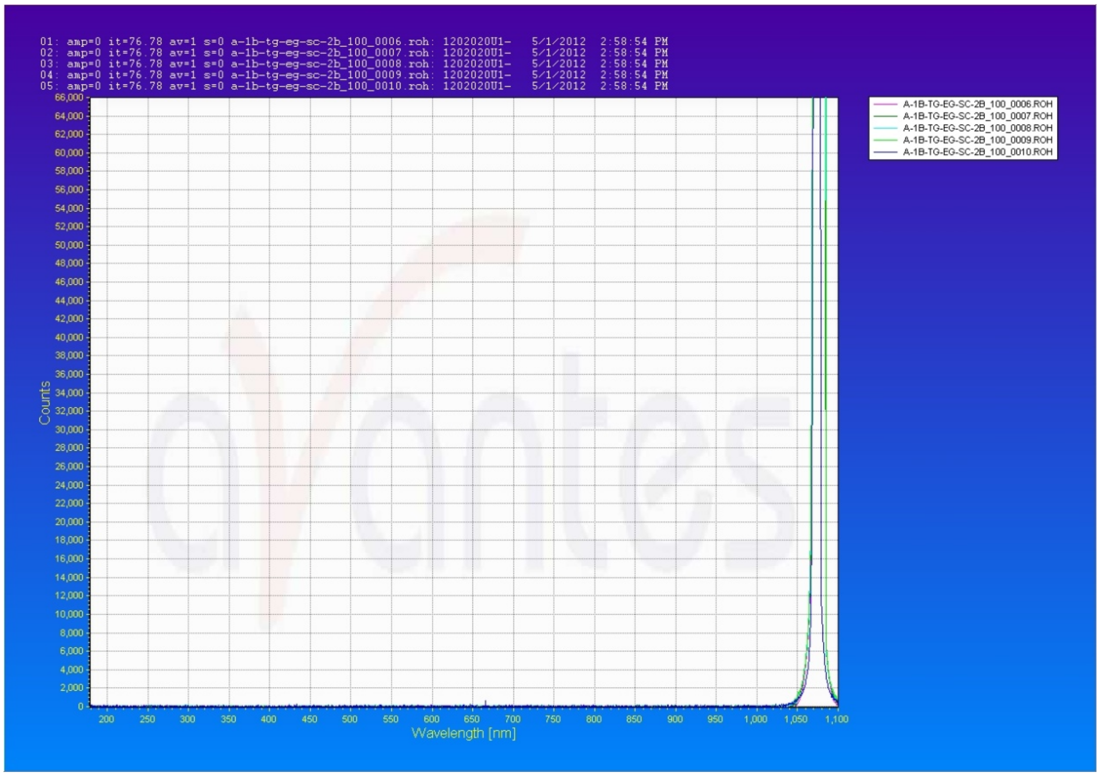

Figure 47. Upper Primer Layer Response at 6000W (100% Laser Power)

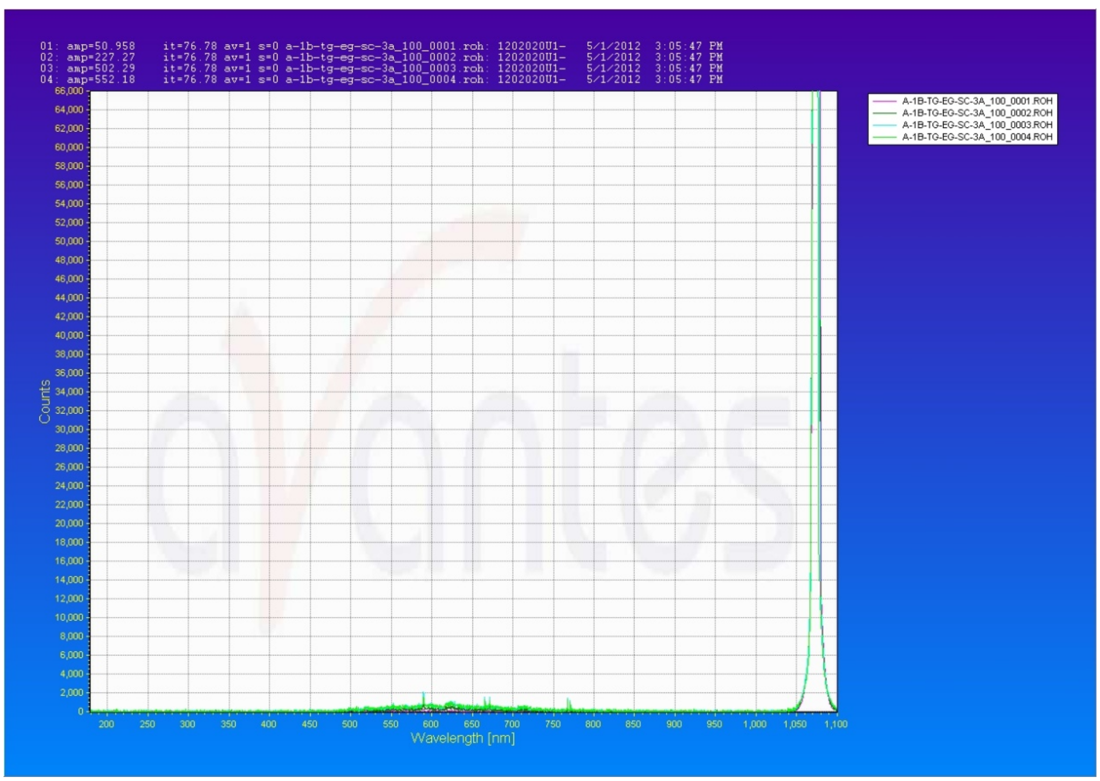

Figure 48. Tan CARC Response at 6000W (100% Laser Power)

As can be seen in the previous 4 figures, only a slight difference in spectral response exists between the coatings. It is possible, with the use of sensor gain adjustment, that the spectral response (between 500 and 800nm) of the CARC layer could be amplified enough to be useful. However, since no difference can be seen at lower power levels, the control system would not be complete and it is extremely doubtful that Goal #2 could be met with a spectral sensor system. Also, as discussed previously, a spectral sensor system would not be effective to control the partial removal of a single layer (Goal #3).

System D Results Summary: With the possible exception of the green and tan CARC topcoats at 100% laser power, the spectral responses of all the coatings in the stack-up are nearly identical. Therefore, it is unlikely that spectral sensors will be useful in accomplishing removal Goal #1, #2 or #3. There is no appreciable difference in spectral response between the coating layers at the different power levels to effectively control the laser for selective coating removal using the spectrial information.

SUMMARY: CTC has successfully demonstrated that spectral response sensors can be used as part of a fiber laser coating removal control system to selectively strip some of the coatings of interest. Table 4 summarizes the coating systems and removal goals that may be able to be accomplished using a spectral sensor control system.

Table 4. Spectral Data Summary

Weapon System	Coating System	Removal Goal	Possibly Use Spectral Sensor for Selective Removal
A	OML	Goal #1 – Partial removal of topcoat	No[1]
		Goal #2 – Complete removal of topcoat and leave primer	Yes
B	Coating	Goal #1 – Complete removal of layers above base primer	No
		Goal #2 – Complete removal of boot/adhesive above lower primer layer	No
	OML	Goal #1 – Complete removal of all layers above base primer	No
C	Primer	Goal #1b – Complete removal of all layers above base primer	Yes
	Coating	Goal #1b – Complete removal of all layers above base primer	Yes
		Goal #2 – Partial removal of topcoat	No[1]
	Rain Erosion	Goal #1b – Complete removal of all layers above base primer	Yes
D	Surrogate	Goal #1 – Complete removal of all layers above base primer	No
		Goal #2 – Complete removal of CARC topcoat	No
		Goal #3 – Partial removal of surrogate	No[2]

1. This removal goal will be accomplished with the thickness sensor.
2. This removal goal will be accomplished with the thickness sensor in combination with another sensor that identify when the surrogate coating has been reached.

To assure proper operation, distinct characteristics in the produced/reflected spectra of adjacent coatings must be present in order to differentiate between them. Since this is not always the case, a spectral sensor cannot be solely utilized in every coating scenario. It is anticipated that in order to meet the coating removal goals of the SERDP program, a suite of sensors will be necessary. CTC will soon perform a full evaluation of a non-contact thickness sensor, manufactured by Picometrix, which should greatly enhance selective stripping capabilities.

An investigation is also underway that utilizes a low-wattage green laser to non-destructively illuminate the surface of coatings and may provide sensory information to aid in the distinction of substrates and coatings.

Additionally, CTC will investigate the color recognition camera on the Advanced Robotic Laser Coating Removal System (ARLCRS) robot prototype to see if it can differentiate between the different coating layers. The ARLCRS is currently located at CTC in Johnstown, PA.

TeraHertz Thickness Sensor Optimization
The purpose of this testing was to optimize the Picometrix T-Ray 4000 Terahertz thickness measurement system (see Figure 49).

The following were goals to be accomplished through this Testing effort:

1. Determine how the system will operate for this application
2. Test the sensory system's measurement capabilities for simple coatings
3. Test the sensory system's measurement capabilities for more complex, multi-layer stack-up coatings
4. Determine the sensitivity of the system to environmental conditions
5. Optimize the sensor for use with the Fiber Laser system.

Figure 49. Picometrix T-Ray 4000

To accomplish these goals, the following tasking was performed:

1. Determine how the system will operate for this application.
This knowledge was obtained primarily through discussion, hands-on training during system install and startup, and basic vendor demonstration with a stationary sensor. Specific items determined included:

- What operator setup (configuration/calibration) is required and how this is done?
  Results: There are two types of configuration/calibration work:
  a. At initial installation – done using T-Gage configuration server software
     i. Adjustments to obtain optimal signal bandwidth
     ii. Capture reference waveforms to subtract from raw sensor waveform, leaving usable signal
     iii. Capture background baseline for noise cancelation
  b. Setup recipes for each new coating system being measured using T-Gage Client Recipe software application.
     i. Selection of best filter to achieve best waveform features
     ii. Identify the interface reflections in the waveform and drag boxes around them to indicate where the software should look for them

iii. Setup the output calculation formula (takes time readings for the identified interface reflections, and uses them with multipliers to develop output thickness measurement)

- Determine what hardware interface is required (triggers, start/stop, etc.):
  <u>Results:</u> There are no electrical control hardware interfaces; the data is calculated in the measurement server, and output through Ethernet, in comma separated variable (CSV) form. The system can be setup to continuously take readings and stream the data. This Ethernet data stream is slow enough that it can be connected through a network/switch to the client server for viewing and other systems (such as our Ethernet-to-analog interface).

- How does the operator/system interact during actual use – manual start/stop, data file naming, data file retrieval, data file viewing/interpretation?
  <u>Results:</u> The system can be instructed to begin operation and stream data through the client software application. It can simply continue running in this fashion until a change in recipe is required, at which point the user can select and execute a different recipe. The operator can use the client software application capture streamed measurement data and save it to a .CSV file (which the operator can name). The data capture start/stop and file naming is accomplished through typical data acquisition commands available in the application.

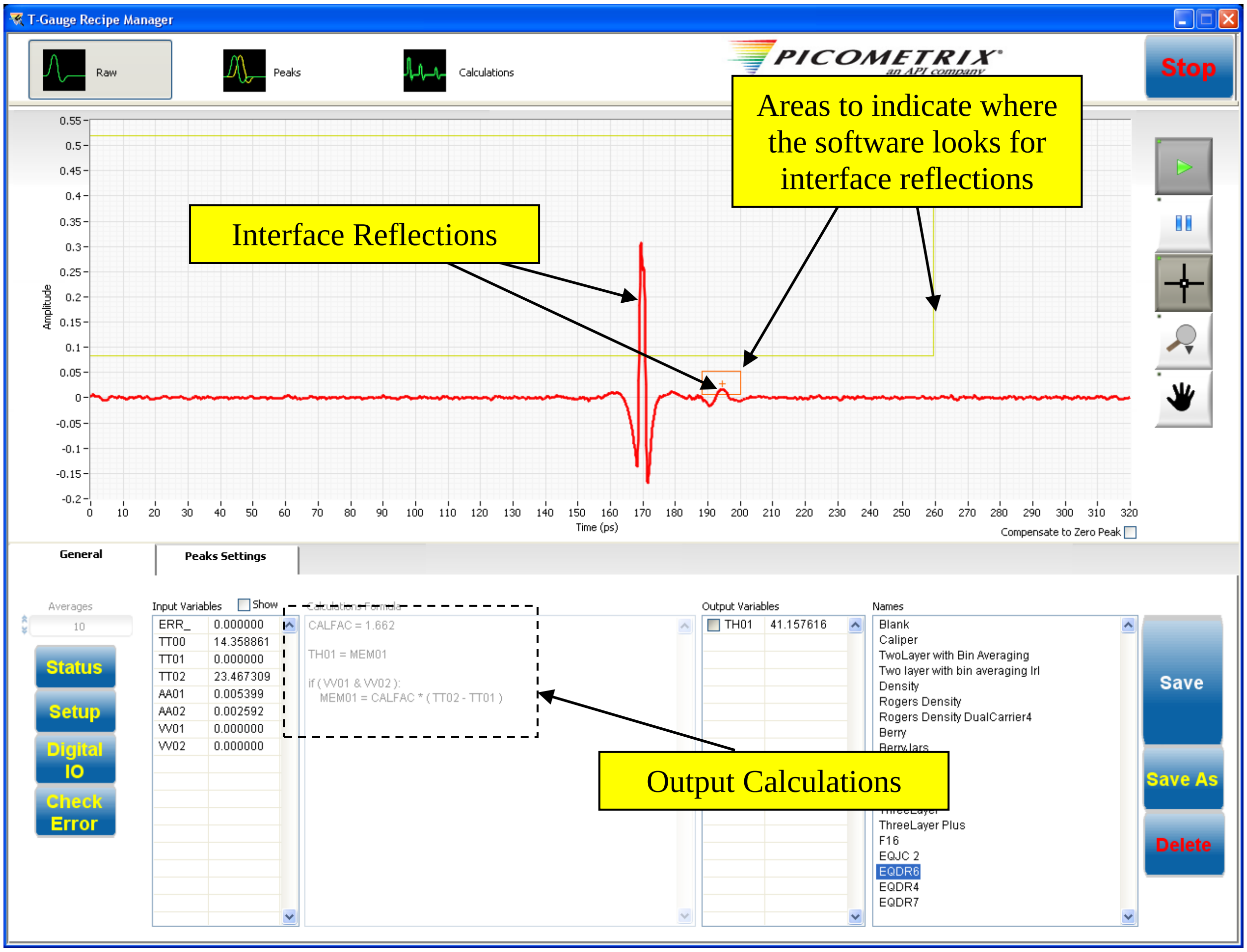

Figure 50. Picometrix Recipe Setup

- Can the system recognize and report back on multiple coating layer thicknesses, or just total?
  <u>**Results:**</u> In some cases, it is possible to recognize and measure more than one layer thickness, but this is only possible if there is a significant difference in index of refraction between the two layers. If two layers are too close in index, they will appear as a single layer. Also if a layer is too thin, the interface reflections may be so close together that the numerical sensor algorithm cannot separate the two enough to measure. In this case the two interface reflections are sensed as only one.

- What does the system recognize as the bottom interface – aluminum substrate/graphite epoxy substrate/conductive coating layer?
  <u>**Results:**</u> The Aluminum substrate, graphite epoxy substrate, or a conductive coating layer will all appear as the bottom (final) interface reflection. Each of them will stop the signal. Whichever of these 3 items the terahertz pulse reaches first will be the bottom (final) interface reflection.

- Are separate setups/calibrations required for each different coating stack-up?
  Results: Yes, although it may be possible for one recipe to handle more than one if there are appropriate similarities.

- Can the system automatically recognize change from one coating stack-up to another? (i.e., if you move from a 2-layer coating to a 5-layer coating, will the system automatically begin reporting on 5 layers?)
  Results: Not normally – limited to special circumstances where the output calculation formula could be made to logically work for both situations. For full implementation in a system such as the mobile robotic laser coating removal system that CTC and National Robotics Engineering Center (NREC) are assembling, it is likely that the software interface will need to prompt the Picometrix sensor to use the correct recipe for the coating stack-up which it is currently being moved over. This assumes stripping system pre-knowledge of what coating stack-ups are present over all areas of the aircraft skin.

2. **The single point sensory system's measurement capabilities for simple baseline coatings (topcoat/primer) were tested (see Figure 51). The following items were determined:**
   - Ability to recognize the two layers
   - Accuracy in measuring the layers
   - Limitations

Figure 51. Picometrix Single Point Thickness Sensor

Testing procedure:

a. Mark the location of pre-measured points on the top surface of the test sample

b. Move the robot over the table so that the Picometrix sensor head is the appropriate standoff distance above the table surface. Place the sample on the table with a point immediately below the sensor.
c. Start T-Ray acquisition
d. Record the T-Ray thickness measurement, along with the pre-measured thickness.
e. Move the sample to the location of the next data point
f. Repeat the procedure
g. After completion, review the data and compare to known coating thicknesses

Table 5. Simple Baseline Coating Test Results

Panel ID	Layers	Measurement Points	Painted Thickness (inches)		Sensor Measured Thickness (mils)	
			Top Layer	Total Layers	Top Layer	Total Layers
EQJC #2	2 – Full Stack	1	0.0071	0.0083	Could not measure top layer individually	8.3
		2	0.0079	0.0091		8.1
		3	0.0075	0.0087		8.7
		4	0.0077	0.0089		8.8
		5	0.0071	0.0083		
		6	0.0076	0.0088		
		7	0.0070	0.0081		
		8	0.0069	0.0081		
		9	0.0078	0.0090		
		Average	0.0074	0.0086		

Result Comments:
Hooked up single point system to robot using the 1.5” diameter and 6” focal length lens. Moved panel so the sensor measured over each “measurement point” on the panel. Sensor could not see the primer layer individually, but saw the total coating thickness of the two coatings combined.

3. Test the single point sensory system’s measurement capabilities for more complex, multi-layer stack-up coatings:

- Ability to recognize the layers
- Accuracy in measuring the layers
- Limitations

Testing procedure:

a. Mark the location of pre-measured points on the top surface of the test sample
b. Move the robot over the table so that the Picometrix sensor head is the appropriate standoff distance above the table surface. Place the sample on the table with a point immediately below the sensor.
c. Start T-Ray acquisition
d. Record the T-Ray thickness measurement, along with the pre-measured thickness.
e. Move the sample to the location of the next data point
f. Repeat the procedure
g. After completion, review the data and compare to known coating thicknesses

Table 6. Multi-Layer Stack-Up Coating Test Results

Panel ID	Layers	Measurement Points	Painted Thickness (inches)					Sensor Measured Thickness (mils)	
			1st Layer (133+590)	2nd Layer (133+497)	3rd Layer (133+591)	Total Layers	Total Layers 2+3	Trial #1 (Layers 2+3)	Trial #2 Repeatability (Layer 2+3)
EQDR #6	6 – Full Stack	1	0.0038	0.0376	0.0033	0.0447	0.0409	40.9	41.0
		2	0.0038	0.0387	0.0033	0.0458	0.0420	40.5	Not measured
		3	0.0036	0.0410	0.0032	0.0478	0.0442	43.5	Not measured
		4	0.0041	0.0360	0.0027	0.0428	0.0387	38.0	Not measured
		5	0.0043	0.0381	0.0028	0.0452	0.0409	40.0	Not measured
		6	0.0033	0.0405	0.0031	0.0469	0.0436	42.5	Not measured
		7	0.0038	0.0366	0.0029	0.0433	0.0395	38.5	Not measured
		8	0.0039	0.0380	0.0029	0.0448	0.0409	40.0	Not measured
		9	0.0036	0.0387	0.0029	0.0452	0.0416	41.0	Not measured
		Average	0.0038	0.0383	0.0030	0.0452	0.0413		

Result Comments:

Trials #1 and #2:
Hooked up single point system to robot using the 1.5” diameter and 6” focal length lens. Moved panel so the sensor measured over each “measurement point” on the panel. Sensor could not see the primer layer individually, but saw the total coating thickness of the two coatings combined.

Layer #1 is a conductive layer – could not measure this layer...sensor saw this as the lowest interface reflection – cannot penetrate deeper - equivalent to a substrate. Layer #2 is a specialty coating, and Layer #3 is a topcoat. Could not determine the thicknesses of layers #2 and #3 individually. CTC believes that with the proper filter control we could have determined these individual thicknesses.

Total layers measured with sensor include both layers #2 and #3. Good correlation between pre-measured thickness and the combined layer readings obtained with the Picometrix.

Table 7. Multi-Layer Stack-Up Coating Test Results

Panel ID	Layers	Measurement Points	Painted Thickness (inches)			Sensor Measured Thickness (mils)	
			1st Layer (133+590)	2nd Layer (133+497)	Total Layers	Trial #1 (2nd Layer)	Trial #2 Repeatability Test (2nd Layer)
EQDR#4	4 layers	1	Conductive layer. Could not measure with sensor so did not list it out.	0.0397	0.0435	40.2	40.25
		2		0.0395	0.0436	40.75	Not measured
		3		0.0389	0.0432	41.0	Not measured
		4		0.0393	0.0433	40.5	Not measured
		5		0.0407	0.0447	43.25	Not measured
		6		0.0395	0.0442	42.25	Not measured
		7		0.0396	0.0437	41.25	Not measured
		8		0.0395	0.0433	41.5	Not measured
		9		0.0391	0.0439	41.75	Not measured
		Average		0.0395	0.0437		

Result Comments:

Note: total coating thickness includes the conductive layer #1

Trials #1 and #2:
Still using single point system hooked up to robot using the 1.5” diameter and 6” focal length lens. Moved panel so the sensor measured over each “measurement point” on the panel. Sensor could not see the primer layer individually, but saw the total coating thickness of the two coatings combined.

Used same calibration from EQDR#6 panel.
Sensor total thickness based on 2nd layer (which includes topcoat and primer under this material)

Table 8. Multi-Layer Stack-Up Coating Test Results

Panel ID	Layers	Measurement Points	Painted Thickness (inches)			Sensor Measured Thickness (mils)	
			1st Layer (133+590)	2nd Layer (133+591)	Total Layers	Trial #1 (2nd Layer)	Trial #2 Repeatability Test (2nd Layer)
EQDR #7	4 – Full Stack	1	0.0047	0.0032	0.0079	3.5	3.4
		2	0.0045	0.0033	0.0078	3.9	Not measured
		3	0.0046	0.0030	0.0076	3.5	Not measured
		4	0.0047	0.0032	0.0079	3.7	Not measured
		5	0.0047	0.0028	0.0075	3.55	Not measured
		6	0.0041	0.0029	0.0070	3.8	Not measured
		7	0.0045	0.0031	0.0076	3.55	Not measured
		8	0.0041	0.0030	0.0071	2.95	Not measured
		9	0.0038	0.0029	0.0067	3.5	Not measured
		Average	0.0044	0.0030	0.0075		

Result Comments:

Trial #1:
Still using single point system hooked up to robot using the 1.5” diameter and 6” focal length lens. Moved panel so the sensor measured over each “measurement point” on the panel. Sensor could not see the primer layer individually.

Recalibrated for this panel.

The 1st Layer is a conductive layer, so the sensor does not see through it. Therefore the sensor is only reading the 2nd Layer. During this testing, there was some problem obtaining readings consistently, even though the reflections appeared to be very consistent and recognizable. Irl complained that they have seen this before – blaming it on software issues. The first reflection (going left to right) was smaller than the second reflection. Irl captured raw data to take back to Picometrix for software analysis.

Table 9. Multi-Layer Stack-Up Coating Test Results

Panel ID	Layers	Measurement Points	Painted Thickness (inches)			Sensor Measured Thickness (mils)
			1st Layer (Top+Prim)	2nd Layer (Coating)	Total Layers	Trial #1 (2nd Layer)
2OB-2	Full Stack	7		0.0378		Could not see through the material
		8		0.0458		
		9		0.0504		
		10		0.0365		

Result Comments:

Could not see through material or the other area of the panel that did not have boot. Could not take measurements.

4. Determine the single point system's sensitivity to environmental conditions during actual use:

- Variable standoff distance
- Angular variation with respect to the surface
- Use of air knives
- Determine if there are any negative operational effects while measuring during laser ablation

Testing procedure:

a. Fixture sample to table such that single point sensor head is directly above points of known coating thickness
b. One item at a time – for each test, modify the sensor mounting/robotic program/air knife operation, etc. to make the noted environmental changes
c. Start T-Ray acquisition
d. Record the T-Ray thickness measurement, along with the pre-measured thickness.
e. Repeat the procedure for each of the changed environmental conditions (standoff, angle variation, and air knife operation).
f. For the sensitivity testing to laser ablation, setup an appropriate ablation robotic motion program to move the sensor along this line ahead of the laser ablation line
g. Start T-Ray acquisition
h. Execute robot motion program (with or without laser ablation as desired)
i. Stop T-Ray
j. Save off data for analysis
k. After completion, review the data and compare to known coating thicknesses

Table 10. Multi-Layer Stack-Up Coating Test Results

Environment Effects	Trial #1	Trial #2	Trial #3	Trail #4
Coating Thickness Reading	No Change	No Change	No Change	See Figures 4 through 6
Stand Off	6 inches	5.25 – 7 inch range from surface	6 inches	6 inches
Sensor Angle to Surface	Normal	Normal	Less than +/- 5 deg. variation allowed	Normal
Air Knives	On	Off	Off	On
Laser Ablation	None	None	None	Yes

<u>Results:</u>

<u>Trial #1: Air Knife</u>

Used panel EQDR#6 and initial thickness sensor measurement of 38.5 mils (measurement point 7 taken from Table 2, Trial #1). The air knife was turned on to see if it affected the sensor readings. No effects were seen – obtained the same reading as previous 38.5 mils.

<u>Trial #2: Standoff Distance</u>

Used panel EQDR#6 and initial thickness sensor measurement of 41.0 mils (measurement point 9 taken from Table 2, Trial #1). Placed the panel on an adjustable table and moved the panel up and down to see effects. Obtaining the same thickness readings, but the reflections were shifting right (for greater standoff) and left (for shorter standoff) on the waveshape screen of the sensor software. Anything greater than 7 inches would be off the software screen and anything less than 5.25 inches standoff would be off the software screen as well. Every reading was the same thickness measurement of 41.0 mils. Therefore, with this particular set of hardware and calibration, the single point Picometrix thickness sensor readings are not affected by standoff distance within a range of roughly plus 1-inch to minus 5/8-inches of the nominal standoff of 6-inches. Outside this range of standoff distances, the system does not provide a measurement.

<u>Trial #3: Sensor Angle to Surface</u>
Used panel EQDR#4 for this test. With a 1.5-inch diameter lens and 6-inch standoff, we are limited to angle variation less than 5 degrees from normal. Obtained the same thickness measurements until the sensor angle went beyond 5 degrees. Beyond 5 degrees, the pulse reflection off the panel comes back outside the view of the sensor transmit/receive window.

<u>Trial #4: Laser Ablation</u>
Using a multi-coating panel, we tested the effects of laser ablation during single point measurements. The real-time data was recorded at 100 Hz. Multiple passes of data were recorded before and between ablation passes. Pass #1 was with the laser off to compare the micrometer thickness readings to the sensor thickness measurements (see Figure 52). Pass #2 was a repeat of Pass #1. Pass #3 was with laser running. Pass #4 was with laser off but measuring remaining paint thickness (see Figure 53). For both Pass #3 and #4 there were sections where there were no thickness measurement readings ("dead spots"). The Picometrix representative (Mr. Irl Duling) hypothesized that the pulse reflection peak went outside the data capture window. The software window was then re-sized to make it bigger. Then several dry runs were completed to look for dead spots. The sensor output calculation formula (operator entered), was set up (by Picometrix) to maintain the last reading until a new one is sensed. This makes the sensor dead spots appear as flat plateaus in the data graphs. Is Picometrix readings being interrupted because of laser ablation? No - according to Irl Duling.

Passes #5 through #8 were completed and we continued to see data dead spots. It was determined that some of the dead spots were where it went over primer area and sensor couldn't pick up the primer. In its current configuration, it appears that the single point sensor is incapable of reading thickness when the coating gets down to 3-4 mils above substrate. See Figure 54.

Why is some of the data missing? It was concluded later that for single point measurements, anything less than approximately 4 mils of coating thickness does not produce a reflection of sufficient amplitude to be discernable from the large reflection created by the aluminum substrate, when this close (close because of thin remaining coating thickness). Mr. Duling indicated that there are some improvements and tradeoffs that can be made to the system to improve upon this minimum coating thickness measurement limit. A few improvements mentioned include better antenna design, better signal to noise ratio on the receiver, and some transceiver optics design changes. The optic design changes may cause other deficiencies, so Picometrix will discuss these engineering tradeoffs in their feasibility testing report.

Table 11. Coating Thickness for Laser Ablation Environmental Test for Single Point Sensor

Measurement Points	Painted Thickness Measurement (mils) Measured with Positector	
	Initial	After 2nd Strip Pass
1	11.1	3.4
2	10.3	2.4
3	10.4	2.6
4	10.2	2.6
5	11.5	3.7
6	10.1	2.5
7	9.9	2.2
8	10.6	2.7
9	9.7	2.1
10	10.3	2.6
11	10.1	2.4
12	9.8	2.3
13	10.5	2.4
14	10.1	2.5
15	11.4	3.6

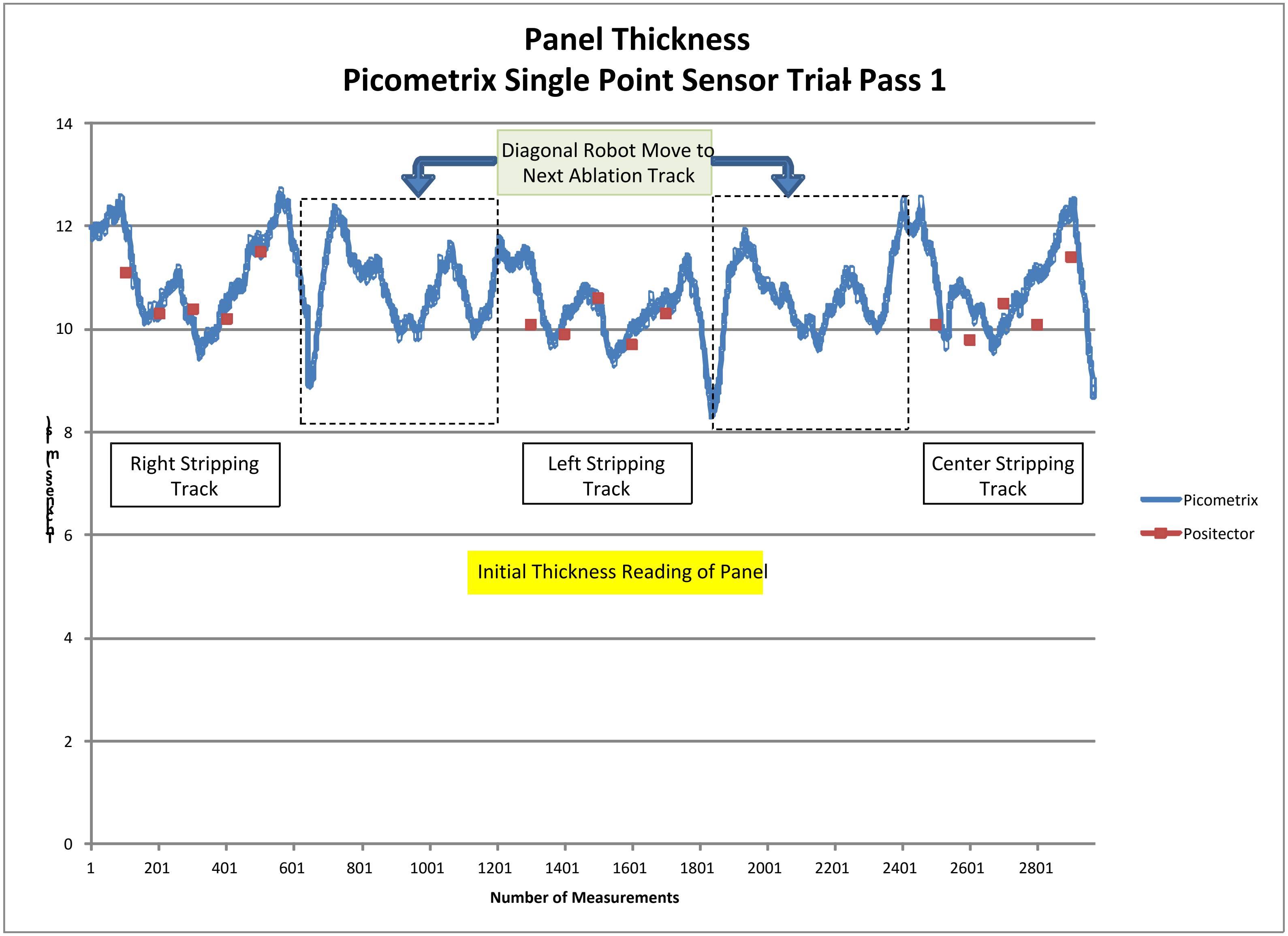

Figure 52. Environmental Tests with Single Point System – Trial #4 – Pass #1

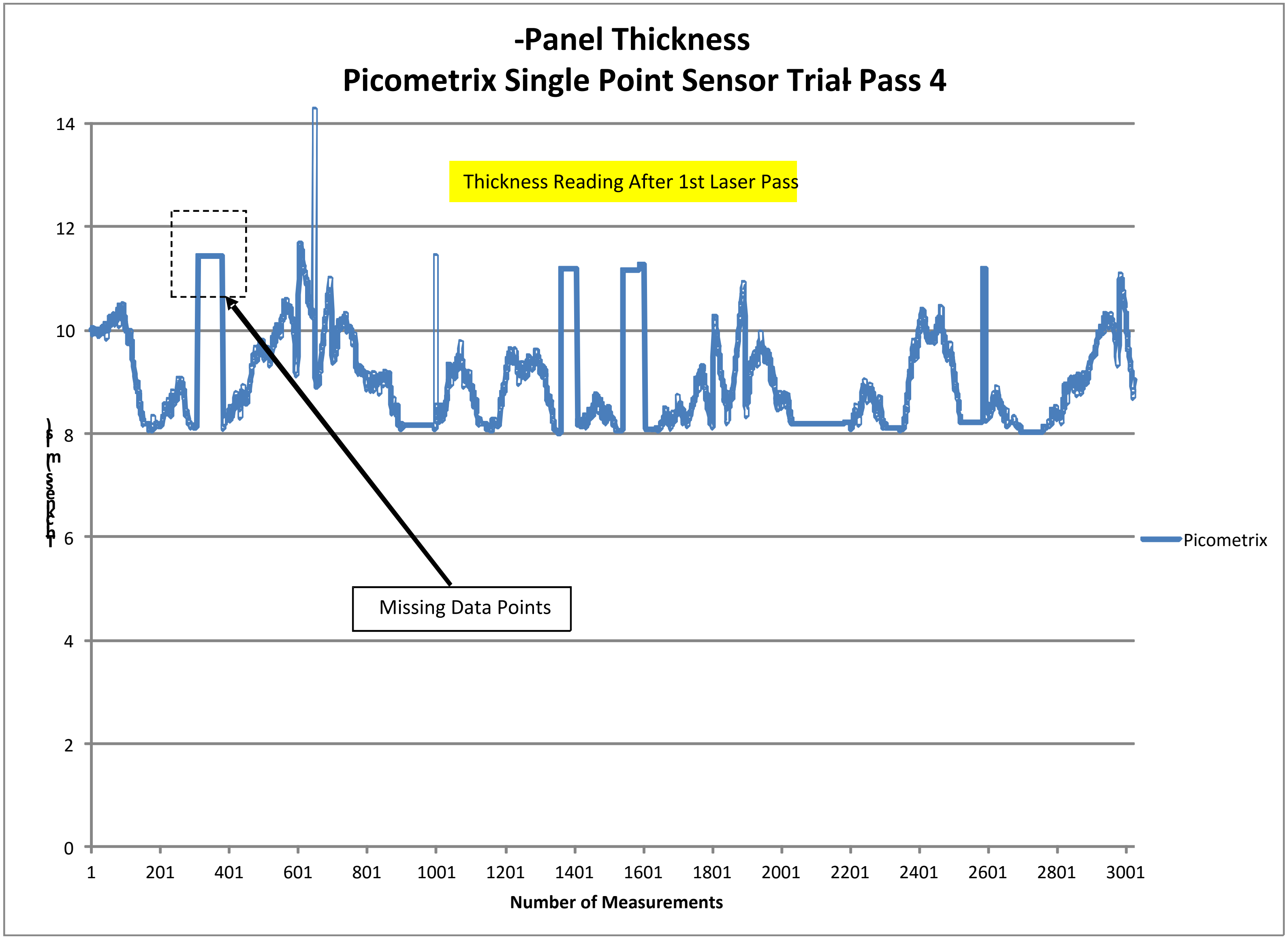

Figure 53. Environmental Tests with Single Point System – Trial #4 – Pass #4

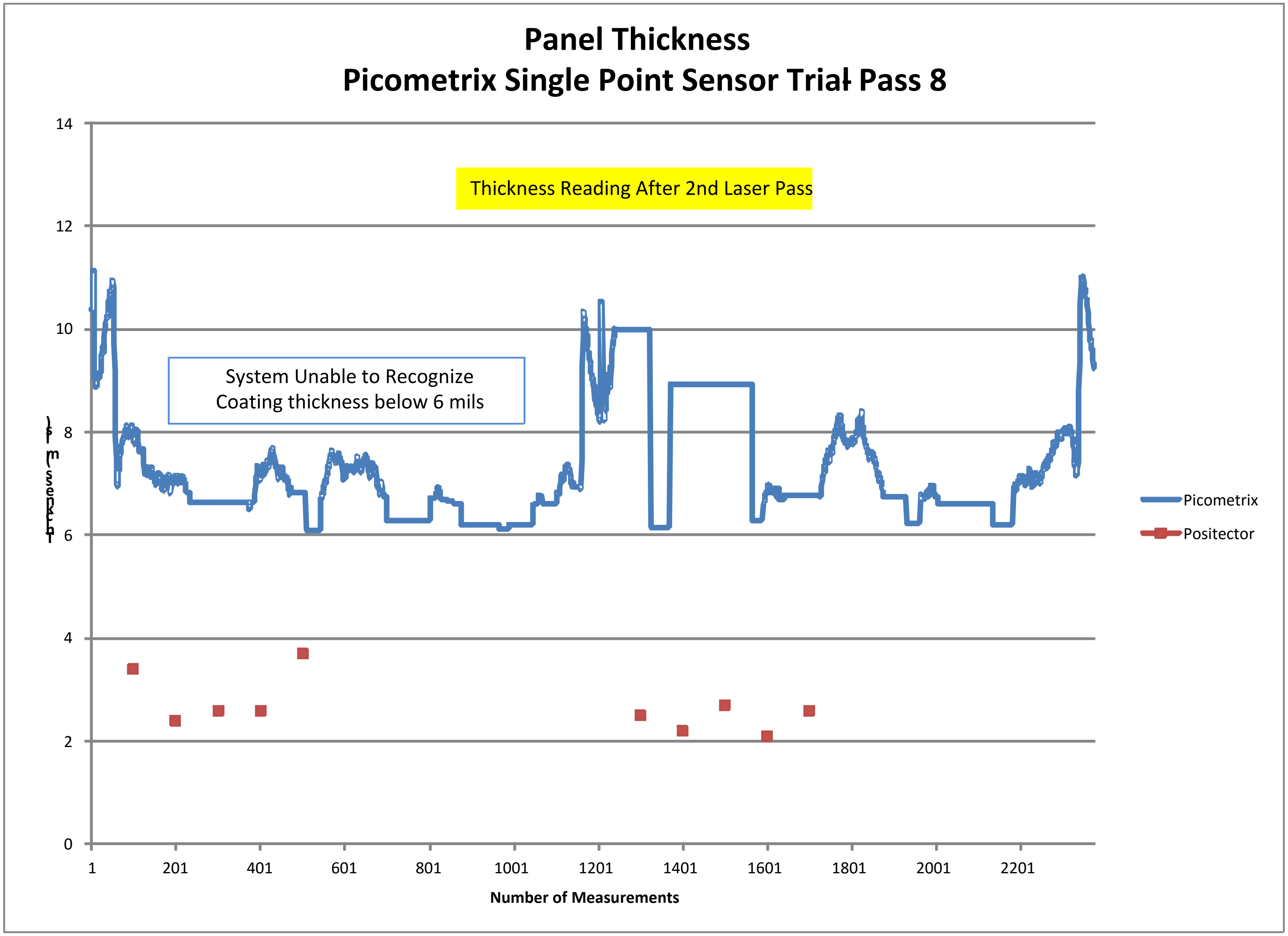

Figure 54. Environmental Tests with Single Point System – Trial #4 – Pass #8

5. **Determine the scanner system's sensitivity to environmental conditions during actual use:**
   - Variable standoff distance
   - Angular variation with respect to the surface
   - Determine if there are any negative operational effects while measuring during laser ablation

Figure 55. Picometrix Scanner Sensor

Testing procedure:

a. Fixture sample to table such that scanner sensor head is directly above points of known coating thickness
b. One item at a time – for each test, modify the sensor mounting/robotic program, etc. to make the noted environmental changes
c. Start T-Ray acquisition
d. Record the T-Ray thickness measurement, along with the pre-measured thickness.
e. Repeat the procedure for each of the changed environmental conditions (standoff, angle variation, and air knife operation).
f. For the sensitivity testing to laser ablation, setup an appropriate ablation robotic motion program to move the sensor along this line ahead of the laser ablation line
g. Start T-Ray acquisition
h. Execute robot motion program (with or without laser ablation as desired)
i. Stop T-Ray
j. Save off data for analysis

k. After completion, review the data and compare to known coating thicknesses

Table 12. Changing Environment Test Results for Scanner Sensor

Environment Effects	Trial #1	Trial #2	Trial #3a	Trial #3b	Trial #3c	Trail #4
Coating Thickness Reading (40.5 mils baseline)	41.0 mils	41.0 mils	41.5 mils	No reading	40.2 mils	See Figures 8 through 12
Stand Off	6 inches 6.25 in 6.5 in 6.75 in 5.75 in 5.5 in	6 inches	6 inches	6 inches	6 inches	6 inches
Sensor Angle to Surface	Normal	Less than +/- 5 deg. variation allowed	Normal	Normal	Normal	Normal
Air Knives	Off	Off	Off	Off	Off	On
Laser Ablation	None	None	None	None	None	Yes

<u>Results:</u>

<u>Trial #1: Standoff Distance</u>
Used panel EQDR#6 and initial thickness sensor measurement of 40.5 mils (measurement point 2 taken from Table 2, Trial #1). Placed panel on adjustable table and moved panel up and down to see effects. Nearly constant thickness readings, but the reflections shift right (for greater standoff) and left (for shorter standoff) on the waveshape screen of the sensor software. Anything greater than 6.75-inches was out of range. Anything less than 5.5-inch standoff was out of range. Every reading was either of 41.5 mils or 42.0 mils. Conclusion: with this particular set of hardware and calibration, the scanned Picometrix thickness sensor readings are not affected by standoff distance within a range of roughly plus 0.75 inches (3/4-inch) to minus 0.5 inches (1/2-inch) of the nominal standoff. Outside this range of standoff distances, the system does not provide a measurement.

<u>Trial #2: Angular Variation</u>
Used panel EQDR#6 for this test. With the scanner tested by Picometrix, we are limited to angle variation less than 5 degrees from normal. We were reading the same thickness measurement until the angle went beyond 5 degrees. Beyond 5 degrees, the pulse reflection off the panel comes back outside the view of the sensor transmit/receive window.

<u>Trial #3: Thickness Measurement Comparison to Single Point System</u>
Tested the accuracy of the scanner sensor compared to the thickness readings of the single point system on various coating types.

<u>Trial #3a</u>: Measured Point#2 on panel EQDR#6. Single point sensor system read 40.5 mils and the scanner sensor system read 41.5 mils.

Trial #3b: Measured Pt#2 on panel EQDR#7. Single point sensor system read 3.9 mils and the scanner sensor system was unable to measure this point.

Trial #3c: Measured Pt#2 on panel EQDR#4. Single point sensor system read 40.75 mils and scanner sensor system read 40.2 mils.

Trial #4: Laser Ablation
Used an multi-coating panel (panel ID: Fiber-AL-2A-APC(DEFT)-1-Practice 43) for these tests. The scanner was running at 5 Hz. Recorded real-time data at 100 Hz. Multiple passes of data were recorded before and between ablation passes. Laser ablation appeared to have no effect on the thickness sensor operation, but as was seen with the single point sensor, when the coating became too thin, it lost the ability to take thickness measurements. Whereas the single point sensor stopped reading at about 4 mils of paint, the scanner stopped reading between 6 and 7 mils. Also found that as the correct reflection receded, the software was using another one, which inadvertently caused the thickness readings to go back up. Concluded that for scanner measurements, anything less than approximately 6 to 7 mils of coating thickness does not produce a reflection of sufficient amplitude to be discernable from the large reflection created by the aluminum substrate, when this close (close because of thin remaining coating thickness). A few improvements mentioned include better antenna design, higher antenna drive power, better signal to noise ratio on the receiver, and some transceiver optics design changes. The optic design changes may cause other deficiencies, so Picometrix will discuss these engineering tradeoffs in their feasibility testing report.

Graphs for the scanner sensor appear in Figures 56 – 60 on the following pages. The data clearly confirms that these sensors will have difficulty measuring coating thicknesses below 6 mils.

Table 13. Coating Thickness for Laser Ablation Environmental Test for Scanner Sensor

[Panel ID: Fiber-AL-2A-APC(DEFT)-1-Practice 43

Measurement Points	Painted Thickness Measurement (mils) Measured with Positector			
	Initial	After 1st Strip Pass	After 2nd Strip Pass	After 3rd Strip Pass
1	10.6	8.8	6.6	4.6
2	10.0	7.7	5.8	3.3
3	9.5	7.4	5.2	3.4
4	10.5	8.6	6.5	4.5
5	10.6	8.4	6.2	4.4
6	8.9	7.2	5.1	3.3
7	9.9	8.1	5.8	3.8
8	9.3	7.1	4.8	2.9
9	9.7	7.8	5.6	3.5
10	9.9	7.9	5.8	3.7
11	10.3	8.2	6.0	4.1
12	10.2	8	6.0	3.8
13	10.2	7.6	5.2	3.3
14	10.0	7.9	5.8	4.0
15	10.9	8.8	6.4	4.7

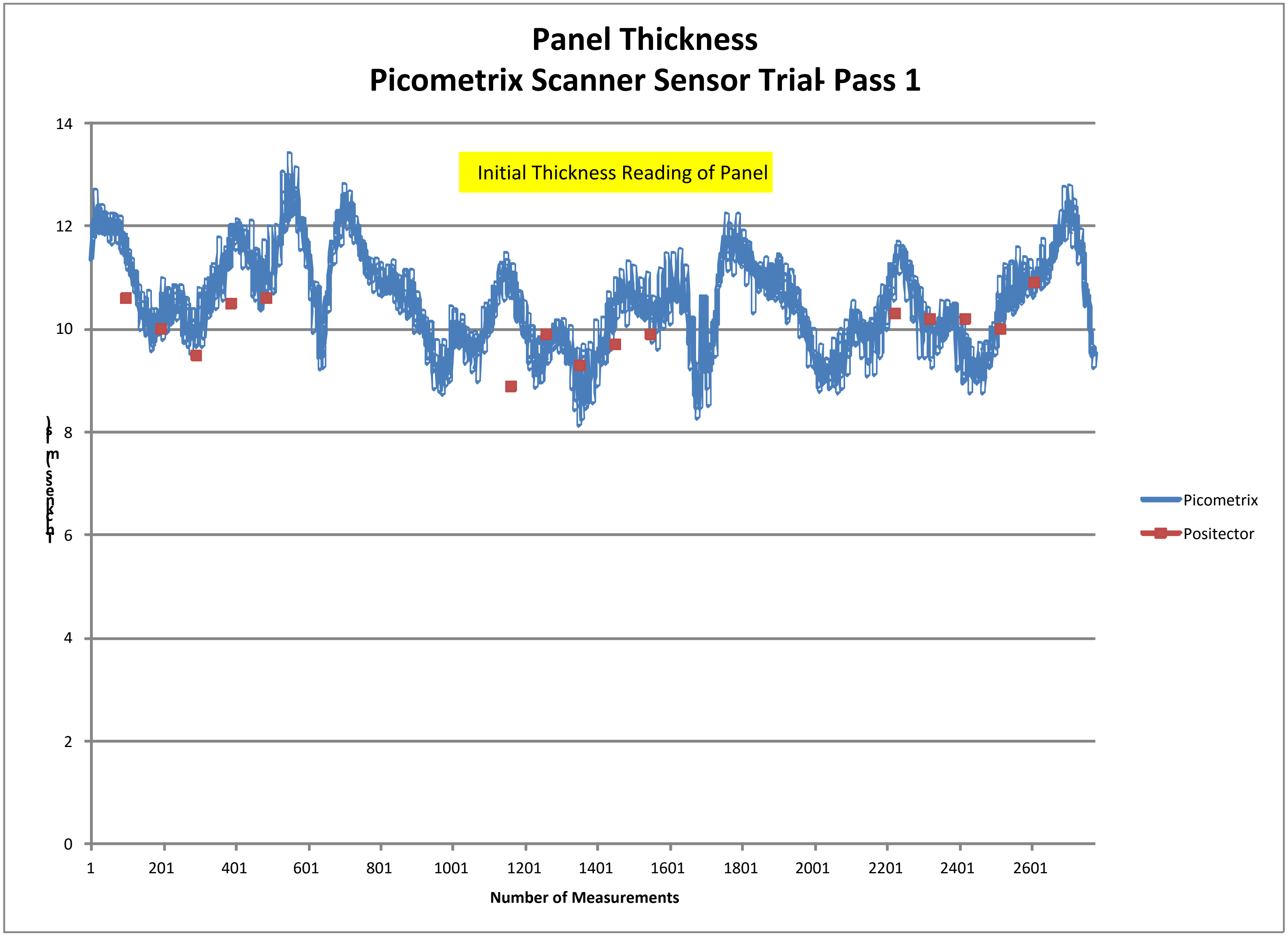

Figure 56. Environmental Tests with Scanner System – Trial #4 – Pass #1

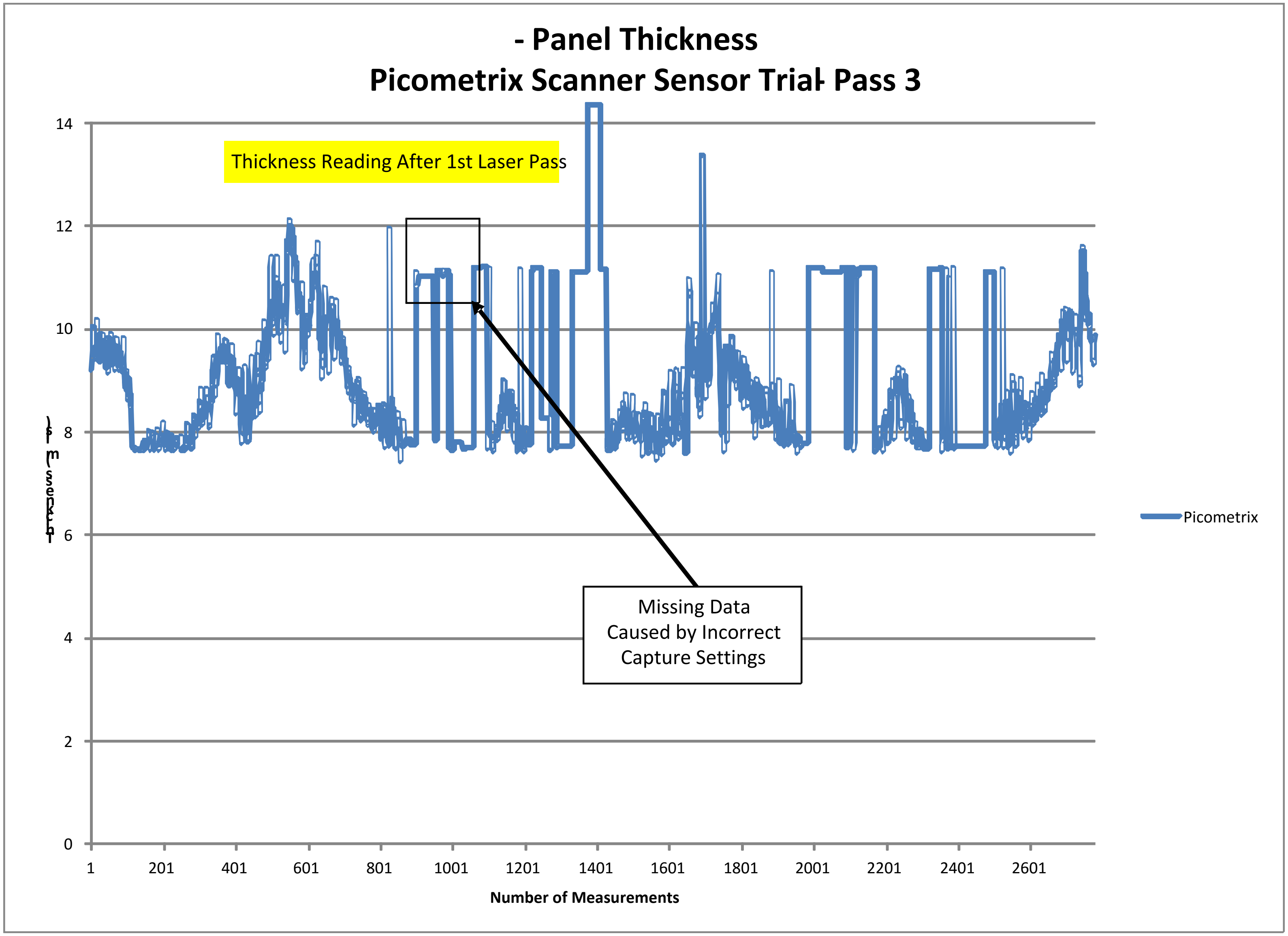

Figure 57. Environmental Tests with Scanner System – Trial #4 – Pass #3

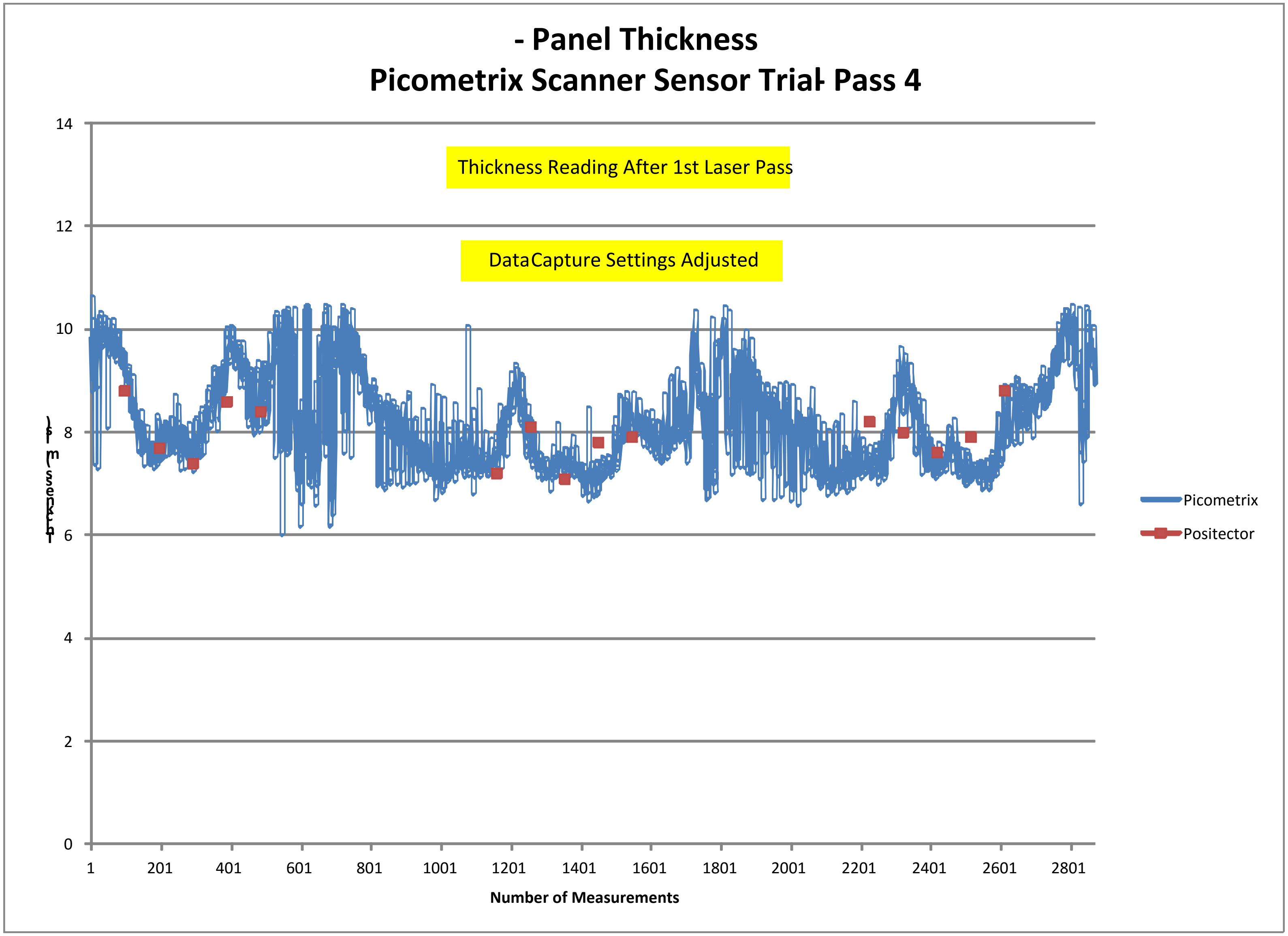

Figure 58. Environmental Tests with Scanner System – Trial #4 – Pass #4

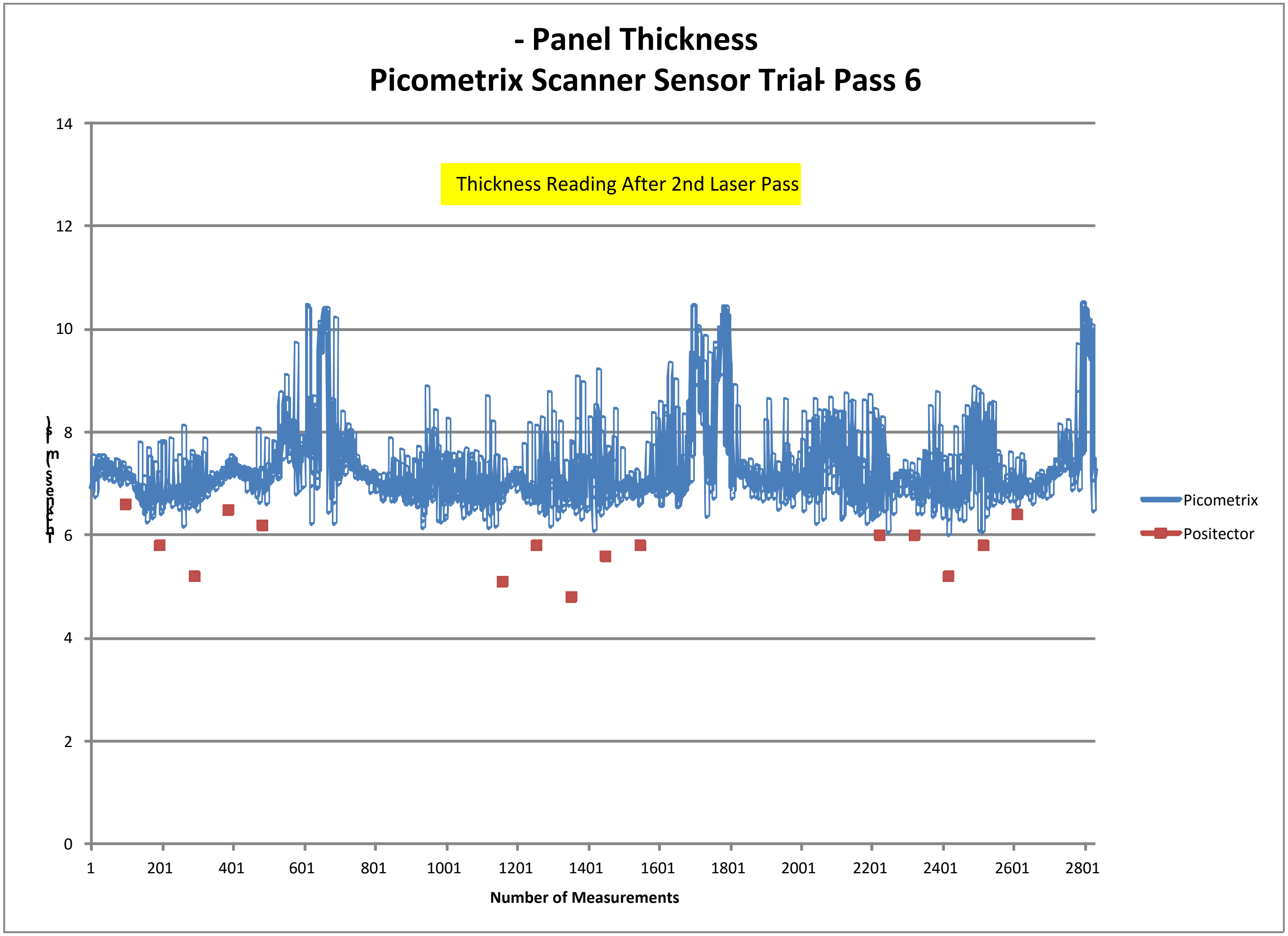

Figure 59. Environmental Tests with Scanner System – Trial #4 – Pass #6

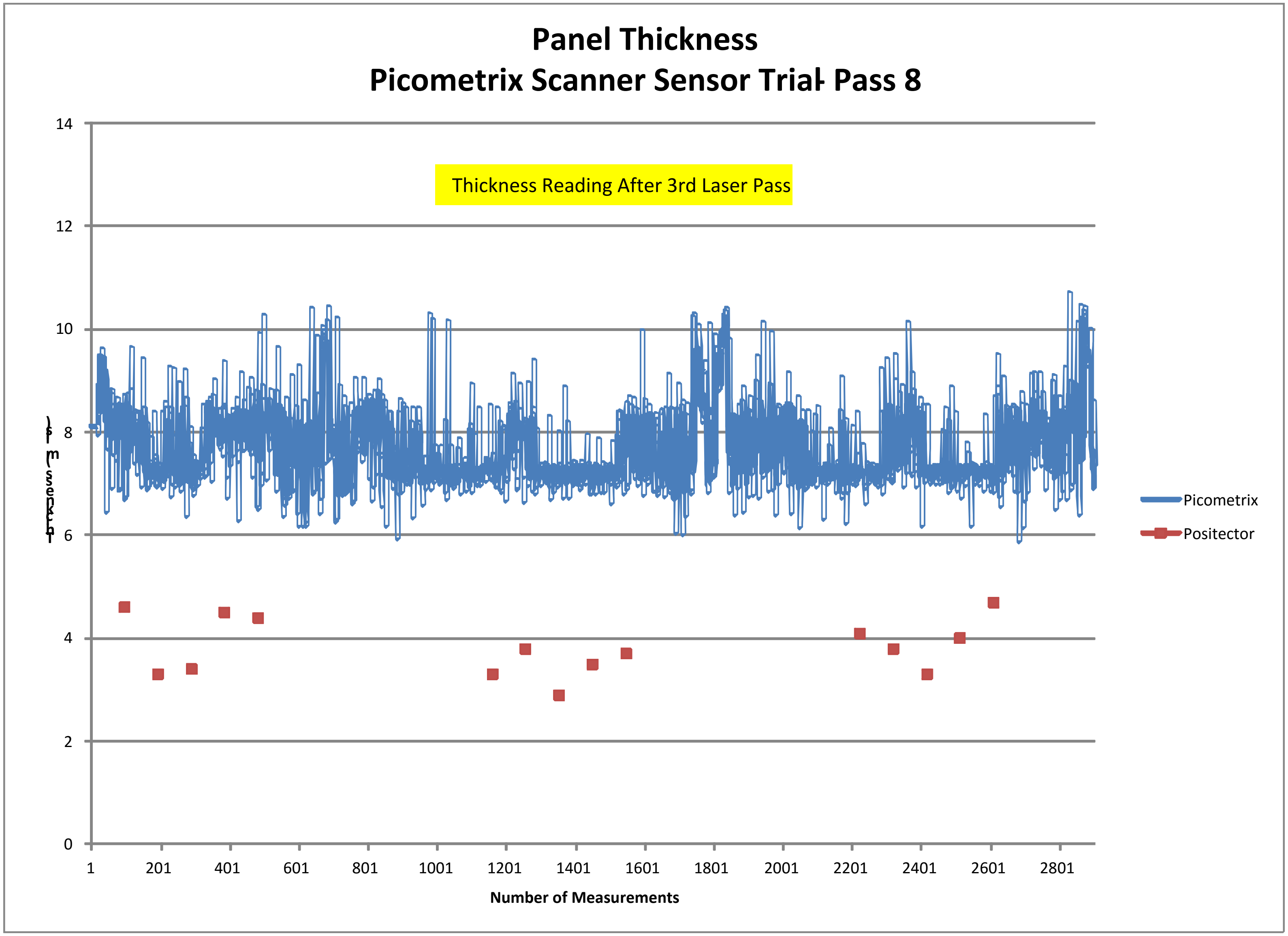

Figure 60. Environmental Tests with Scanner System – Trial #4 – Pass #8

Summary:

This summary briefly describes the capabilities and limitations of the Picometrix T-Ray 4000 Scanner thickness sensor system in the context of how this system can be utilized in the removal or partial removal of coatings of interest to this project. It is assumed that the scanner version of the T-Ray 4000 will be procured (vs. the single point), since final implementation would require knowledge of the coating thickness across all areas of the surface, rather than a single line of points to represent the approximate 140mm wide stripping path.

Capabilities:

- The system performs coating thickness measurement with no contact to the surface.
- The tested system allowed a range of standoff approximately +/- 1-inch for the 6-inch targeted standoff distance.
- Above minimum coating thicknesses, the sensor provided consistent and repeatable measurements.
- Where measurements were possible, the repeatability was within +/- 0.2 mils. The measurements were very consistent with readings performed by other methods.
- Provided measurements at a 100 Hz rate.
    - For all testing (both the single point system and scanner system) the Picometrix unit was taking readings at 100 samples per second.
- In certain circumstances the system can resolve multiple layers (up to 6 total), and provide measurements of each.
- The scanner version as demonstrated would be able to take measurements down to represent "pixels" roughly 15 mm x 15 mm of surface area (100Hz acquisition with 5Hz complete scan cycle over and back). Improvements to this are available – see below.

Limitations:

- The system is incapable of measuring anything below a conductive layer, or aluminum substrate, or graphite epoxy substrate. The top surface of whichever of these impenetrable layers the sensor sees first becomes the final interface reflection seen by the sensor.
- With the scanner system as currently configured, measurements of coatings less than 6 mils in total thickness were not possible. The single point system could measure down to approximately 3 mils. When ablating coatings, once the measured coating falls below this minimum measurement thickness, the sensor can no longer provide a thickness reading. Improvements are possible – see below.
- The sensor as tested at CTC was not able to measure a thickness through one special material.
- The sensor as tested at CTC was not able to measure a thickness through the conductive coating material.
- Must be kept within 5 degrees of perpendicular to the surface so that the signal reflection returns within the transmitter/receiver aperture.

- The tested system allows a range of standoff distances up to roughly 1" above and below the range mid-point. Outside this range, the sensor does not provide a thickness reading. Increasing the system acquisition rate from 100 Hz to 1000 Hz will reduce this by a factor of one half (1/2" above and below).
- Each particular coating stack-up requires a specific setup/calibration/recipe. The user must setup the system using a known sample. The user must know what stack-up is presently being measured, and select an appropriate recipe for that measurement.
- Providing measurements for multiple layers is limited to cases where the layers have significant difference in index of refraction. Also, individual layers less than several mils will not be discernible from the others immediately adjacent. For example, the primer layers are not discernible and are "added" to the thickness measurement of the coating layer directly above that primer so that those two layers combined are seen by the sensor as one layer. It is also necessary in some cases to use different measurement recipes to get the thicknesses of various layers (i.e. in some cases different filtering selections are required to accentuate the reflections of the individual layer reflections).

<u>Potential Improvements:</u>

- Going from the current data acquisition rate of 100 Hz to 1000Hz, the high speed scanner would be able to take measurements down to represent "pixels" roughly 5 mm x 5 mm of surface area (1000Hz acquisition with 20Hz complete scan cycle over and back). However this rate increase will also reduce the current standoff range by a factor of ½.
- Some improvement in bandwidth is possible through better alignment, optimization of focus, and potential antenna selection change. Increased bandwidth will allow thinner minimum coating layer thickness measurements.
- A Type 2 antenna was used in testing at CTC. A Type 1 High Power antenna may be advantageous to allow better penetration for difficult coatings such as the target specialty coatings used in the SERDP projects.
- Irl Duling (Picometrix representative who performed the testing) has indicated that there are some software limitations (only a few discrete choices in sensor filter setup) which may be improved to provide more flexible recipe setups.

3.2.5 Laser Removal Optimization Testing

Once the sensors were integrated and the control interface created, optimization of the laser parameters was performed for each specialty coating system investigated under this project. The laser parameters were adjusted to achieve the desired coating removal at the fastest strip rates possible while maintaining appropriate substrate temperatures.

The optimization testing determined that some coating systems would require another sensor technology to achieve selective coating removal. This is due to an overlap of the emission values, as detected by the SEM sensor, from the different coating layers within each of those coating stack-ups. As a result, further selective coating removal activities were accomplished

using the ARLCRS technology that uses both the SEM and the surface property analyzer (SPA) sensor.

The SPA sensor system is a color recognition sensor system that discriminates coatings prior to laser ablation by analyzing camera imagery with computer vision and machine learning techniques. The primary purpose of the SPA is to provide a classification and confidence level of the aircraft surface model. To accomplish this, multiple cameras, each with a different filter, and light emitting diode lights are used in a flexible design configuration, as shown in Figure 61, to allow the discrimination of surface coatings and substrate. The SPA system is a software-based system whose flexibility allows for adaption of new coating classes using machine-learning algorithms.

Figure 61. SPA Camera Pod on ARLCRS

The information provided by the cameras and sensing software is first mapped into respective surface model cells, in raw format, as shown in Figure 62.

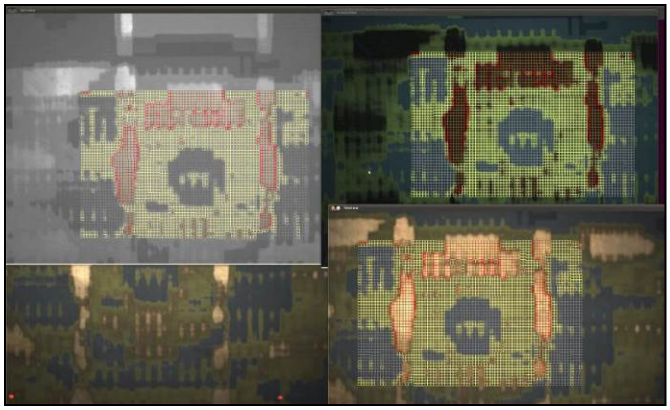

Figure 62. SPA Raw Data

Each cell is subdivided into many equal regions, allowing for detection of much smaller areas of interest. This feature information is then compared to a learned model which provides the classification and confidence level. The laser ablation control program treats the classified surface model cells as pixels on the surface and rasters the laser beam across the surface using the laser scanner control to execute a laser ablation control program. Since the SPA sensor was only available on the ARLCRS, the optimization testing was performed at CTC ETF, as well as OO-ALC.

3.2.6 Optimization Testing Analysis (Go/No Go Decision)

This project identified a Go/No Go decision point to preserve time and resources required for the material and substrate Evaluation Testing effort. The Go/No Go analysis was designed to evaluate the substrates and underlying coatings of optimized panels using coating adhesion tests and cross-sectional microscopy. This Go/No Go analysis was originally designed to be performed in accordance with the "Preliminary and Optimization Test Plan" (Reference 1) at WPAFB. The optimization test panels for one of the weapon system were evaluated in this manner. However, due to project delays, the analysis of the other weapon systems' optimization panels instead involved a visual examination of the remaining coating layers and/or substrate and the proficiency of the laser ablation to reach the desired coating removal goal.

The "Go/No Go Test Report" (Reference 2) outlined the laser coating removal optimization testing and the Go/No Go analysis results. Most of the coating removal goals were deemed a "Go" for laser evaluation testing.

3.2.7 Safety and Occupational Health Testing

Safety and occupation health testing included air sampling and flammability testing, and was performed in accordance with the developed "Safety and Occupational Health Test Plan" (Reference 3). The results of these tests are outlined in Section 4.1.

The air sampling was performed to ensure that airborne contaminants were kept at or below the accepted exposure limits during the fiber laser system evaluation work performed at CTC ETF. The contaminants sampled for included acid mist (hydrobromic acid, hydrochloric acid,

hydrofluoric acid, nitric acid, and phosphoric acid), hydrogen cyanide, isocyanates, nitrogen dioxide, and volatile organic compounds. Air sampling was conducted in accordance with the Occupational Safety and Health Administration (OSHA) or National Institute for Occupational Health (NIOSH) sampling methods, as outlined in Table 14.

Table 14. Air Sampling Methods Used

Sampling Method	Contaminates for Detection
NIOSH method 7903	Acid Mists
OSHA method 42	Isocyanates
OSHA method 182	Nitrogen Dioxide
NIOSH method 6010	Hydrogen Cyanide
OSHA method 215	Hexavalent Chromium
NIOSH method 2549	Volatile Organic Compounds

The air sampling was performed at three locations: (1) the fiber laser operator station, (2) inside the laser stripping cell (adjacent to the process) and (3) at the exhaust vent of the TEKA system, as shown in Figures 63 – 66.

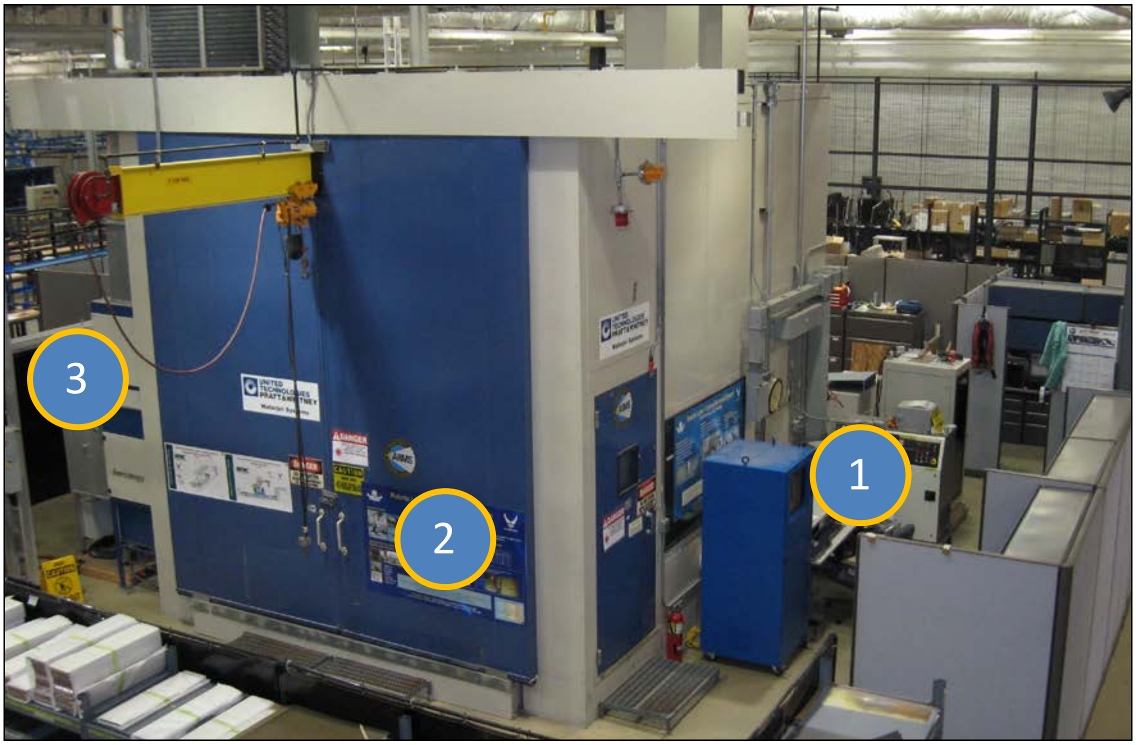

Figure 63. Placement of Air Sampling Pumps

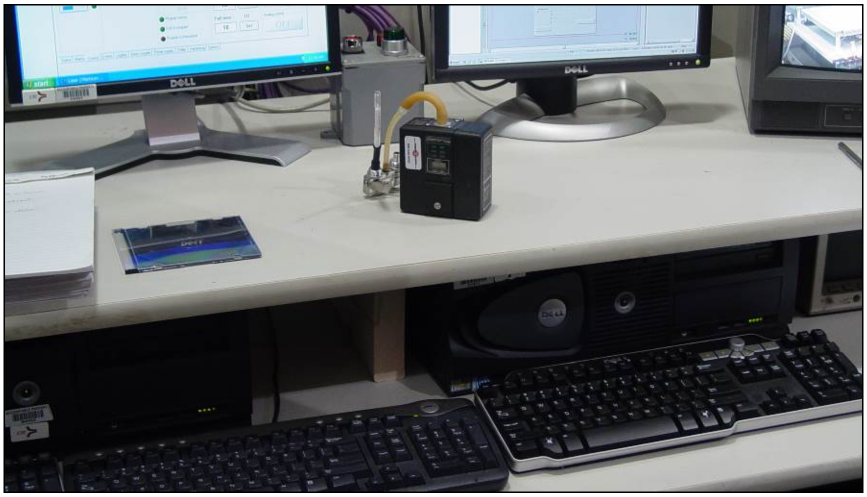

Figure 64. Air Sampling Location 1 – Operator Station

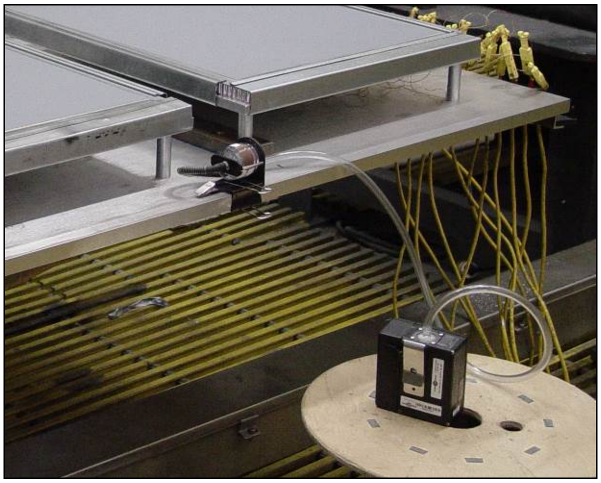

Figure 65. Air Sampling Location 2 – Inside Test Cell

Figure 66. Air Sampling Location 3 – TEKA Exhaust

The flammability testing was performed to evaluate potential explosion or flammability hazards associated with fiber laser coating removal of specialty materials when common aircraft fluids are present. The fluids tested included Engine Lubricating Oil MIL-L-23699 and MIL-PRF-7808, Hydraulic Fluid MIL-PRF-83282 and MIL-H-5606, and JP-8 Turbine Fuel plus Turbine Fuel additive +100. Two types of flammability tests were performed: Surface Contamination and Artificial Cavity.

For the surface contamination test, the test panels were thoroughly wetted with the test fluid to simulate a spill or leak. The fluid was spread evenly over the surface of the test panel and allowed to remain on the test panel for no less than two hours prior to laser ablation.

For the artificial cavity test, a series of four 1/8 inch holes were drilled through each quadrant of the test panel. A small polypropylene beaker, containing the test fluid, was centered directly below these holes and held in place using a test fixture as shown in Figure 67. The test panels were affixed, in a horizontal position, on top of the artificial cavity fixture. The beakers were filled with 1 to 2 ounces of the test fluid during the laser coating removal operation.

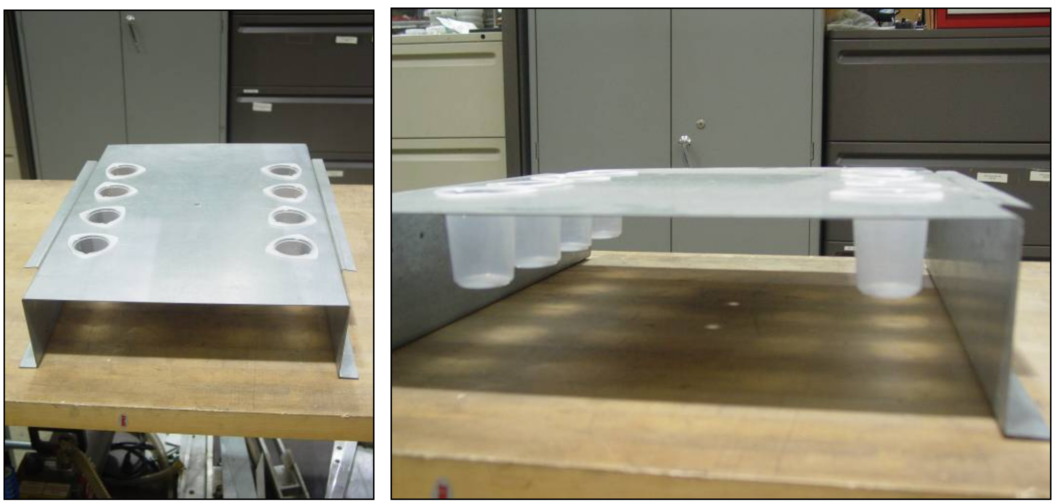

Figure 67. Example Artificial Cavity Fixture

3.3 TASK 3 – Evaluation Testing

The objective of Task 3 was to complete the evaluation laser testing, the evaluation material testing at the designated test facilities, the weapon system specific test reports, and a Final CBA report. Additionally, chromium air sampling and wipe analysis were performed as requested by the SERDP Program Office. These technical activities are described in further detail in the subsections below.

3.3.1 Laser and Material Testing

The evaluation laser testing was performed on flat test panels using the optimized laser parameters established during the optimization testing. The evaluation laser testing for the

coating systems was performed at CTC ETF using the fiber laser system located in the test cell, and for other coating systems were performed at OO-ALC using the full aircraft ARLCRS production unit.

Embedded wire thermocouples were used to monitor substrate temperature response to determine the peak temperature that the top surface of the substrate reaches during the laser coating removal process. Temperature response to the coating removal process is critical in determining potential mechanical or physical property degradation of the immediate substrate or internal components.

After the evaluation laser testing, material testing was performed by Northrop Grumman Corporation. The summary results of the laser and material testing are outlined in Section 4.2.

3.3.2 Final Cost Benefit Analysis

In support of this effort, CTC completed a Final CBA on replacing the current aircraft depainting processes with a robotic laser coating removal system. This CBA summarized the direct costs associated with the current process operations and the potential financial impact of implementing a robotic laser coating removal system at a depot maintenance type facility. The laser depainting scenario within the CBA was based on the evaluation laser test results.

The results of this CBA showed a significant cost savings for various depaint scenarios. When comparing the automated laser removal process to a full aircraft hand sanding process, the laser process was projected to save the depot facility approximately between $3.7 million and $7.4 million annually, depending on production schedules, and provide a capital investment payback period of about 1.4 years. When comparing the automated laser removal process to the combined process of full aircraft wheat starch and chemical stripping, the laser process projected to save the depot facility up to approximately $1.3 mllion annually and provide a capital investment payback period of about 8 years. In addition to the cost savings, there were projected environmental waste disposal avoidances of about 120,000 pounds of spent media and about 18,000 pounds of waste associated with the chemical stripping process.

Implementing the alternative process for replacing the manual baseline process was deemed financially acceptable for most of the weapon systems analyzed. Each weapon system program office will need to evaluate the cost benefit information, as well as other factors, such as material test results, before a final decision is made to implement a robotic laser coating removal system.

3.3.3 Air and Wipe Sampling for Chromium Analysis

At the 2013 SERDP In-Process Review Meeting, the project WP-2146 was given an action item to provide an analysis of the hexavalent chromium and total chromium content for the entire laser stripping process. In February 2014, to address this action item, air samples, wipe samples, and coating debris samples were collected from laser stripping performed on chromium contained aircraft coatings.

Air and wipe sampling for total chromium and hexavalent chromium were completed by at CTC ETF during laser coating removal of test panel coated with chromium contained coating stack-ups. The sampling was performed in accordance with NIOSH Method 7300 for total chromium and OSHA METHOD NO. ID-215 for hexavalent chromium.

Prior to the laser testing, baseline air and wipe sampling were performed to determine baseline levels of chromium and hexavalent chromium at the sampling locations. The laser coating removal was performed using the 6 kW fiber laser system at full laser power.

The air sampling was performed with two GilAir3 sampling pumps equipped with dual adapter tygon tubing allowing hexavalent chromium and chromium to be sampled for simultaneously. The air sampling was performed at three locations: (1) inside the fiber laser test cell as shown in Figure 68, (2) at TEKA exhaust, as shown in Figure 69, which is on top of the TEKA system, and (3) on the operator during and after the laser stripping was completed as shown in Figure 70.

An additional personal air sample was taken at the conclusion of the laser stripping operation to determine operator's exposure to chromium and hexavalent chromium when entering the test cell. The sampling pump on the operator collected for 22 minutes while the individual was in the test cell.

Figure 68. Air Sampling Pump Set-Up Inside Laser Test Cell

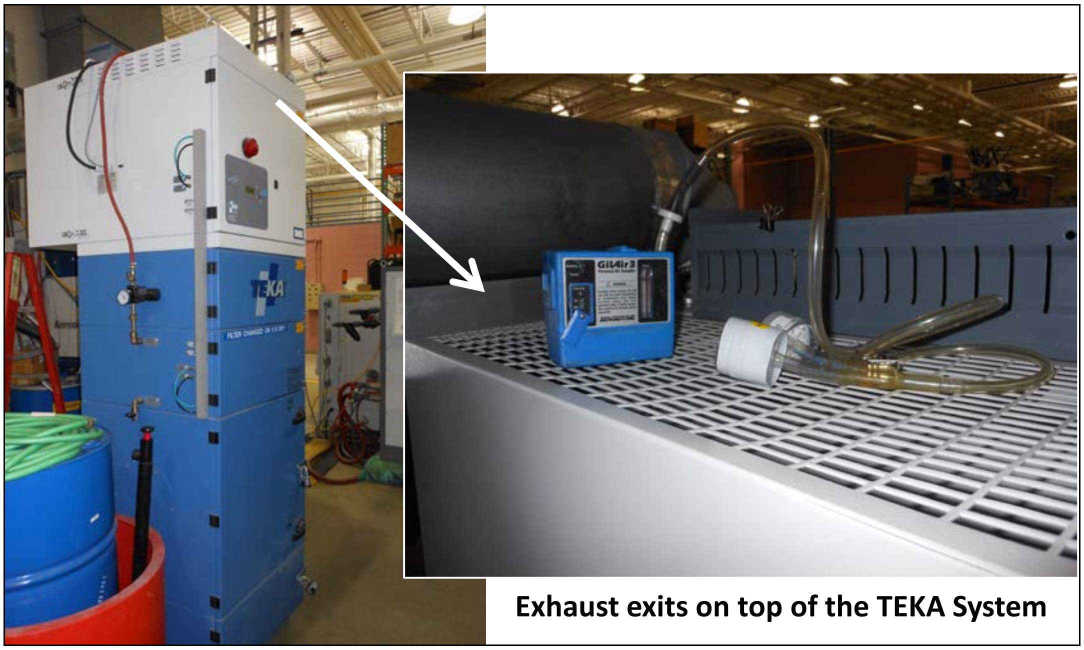

Figure 69. Air Sampling Pump Set-Up at TEKA System Exhaust

Figure 70. Personal Air Sample Located in the Operator's Breathing Zone

The wipe samples for total chromium were collected on a palintest wipe, pre-moistened with deionized water, and the hexavalent chromium wipe samples were collected on a quartz filter. The wipe samples were collected from two locations: (1) on the test table where the fiber laser stripping process occurs inside the laser test cell as shown in Figure 71, and (2) from the TEKA

hopper as shown in Figure 72. The TEKA hopper area was cleaned previously to the baseline samples being taken. In addition, new HEPA filters were installed prior to the baseline sampling. However, the test table was not cleaned prior to baseline wipe sampling which is why the reported chromium levels for the baseline wipe sample were higher than the reported chromium levels for the laser wipe sample.

Figure 71. Baseline Wipe Sample Collected on Table Where Fiber Laser Stripping Process Occurs

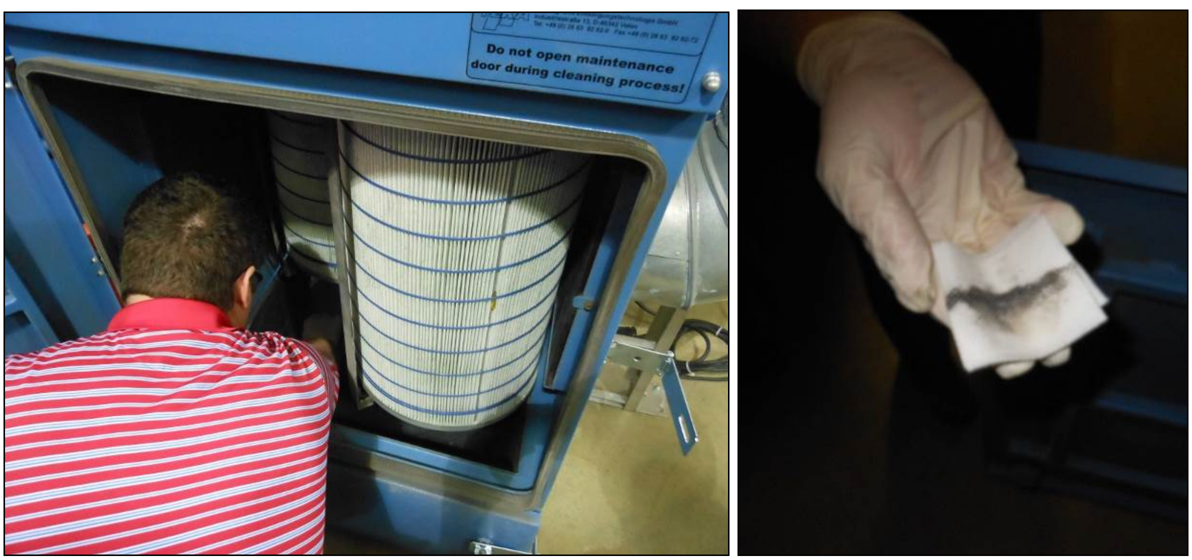

Figure 72. Baseline Wipe Sample Collected From TEKA Hopper

Once the laser stripping was completed, the air and wipe sampling results were analyzed by Bureau Veritas, an American Industrial Hygiene Association certified laboratory. The coating debris was tested at WPAFB. The results from the air sampling testing are reported in Section 4.1.

4.0 RESULTS AND DISCUSSION

4.1 Safety and Occupational Health Results

4.1.1 Air Sampling

Air sampling was performed to ensure that airborne contaminants were kept at or below the accepted exposure limits during the fiber laser system evaluation work performed at CTC ETF. The contaminants tested included acid mist (hydrobromic acid, hydrochloric acid, hydrofluoric acid, nitric acid, and phosphoric acid), hydrogen cyanide, isocyanates, nitrogen dioxide, and volatile organic compounds.

The air sampling results were **below the detection limit** of the analyzing instrument for each contaminant tested, and well below the Permissible Exposure Limit (PEL) for all contaminants measured. The reporting limit is the total weight of particulate the lab can detect during analysis and is expressed in micrograms (μg). The lab determines the concentration for air samples by taking the amount of weight on the sample and divides it by the amount of air drawn through the pump. A summary of the results are reported in Table 15. The air volumes reported from the air pumps ranged between 1.02 and 16.76 Liters for the various air sampling. For each type of air sampling test, the lowest air volumes were used to report the concentrations listed in Table 15 in order to provide the highest possible concentration ceiling. These results were reported in the "Safety and Occupational Health Test Report" (Reference 4).

Table 15. Air Sampling Results

Contaminate	Permissible Exposure Limit	Reporting Limit Weight (μg)	Reported Air Sample Concentration
Acid Mist [/1]			
Hydrobromic Acid	10 mg/m^3 (3 ppm)	2	<0.27 mg/m^3 (<0.081 ppm)
Hydrochloric Acid	7 mg/m^3 (5 ppm)	2	<0.27 mg/m^3 (<0.18 ppm)
Hydrofluoric Acid	2 mg/m^3	2	<0.27 mg/m^3 (<0.33 ppm)
Nitric Acid	5 mg/m^3 (2 ppm)	2	<0.27 mg/m^3 (<0.10 ppm)
Phosphoric Acid	1 mg/m^3	2	<0.27 mg/m^3 (<0.067 ppm)
Sulfuric Acid	1 mg/m^3	2	<0.27 mg/m^3 (<0.17 ppm)
Isocyanates [/1]			
Hexamethylene diisocyanate [/2]	0.035 mg/m^3 (0.005 ppm)	0.2	<0.0128 mg/m^3 (<0.0019 ppm)
Methylene bisphenyl isocyanate	0.2 mg/m^3 (0.02 ppm)	0.2	<0.0128 mg/m^3 (<0.0013 ppm)
Nitrogen Dioxide (NO_2)	9 mg/m^3 (5 ppm)	1	<0.21 mg/m^3 (<0.11 ppm)
Hydrogen Cyanide (HCN)	11 mg/m^3 (10 ppm)	1	<0.14 mg/m^3
Volatile Organic Compounds (VOCs)	NA	50	<14 ppm

ppm = parts per million; mg/m^3 = milligrams of pollutant per cubic meter of ambient air; μg = micrograms.
/1. Concentrations were reported in ppm and converted to mg/m^3.
/2. OSHA does not have a PEL for this material. This is the threshold limit value from the American Conference of Governmental Industrial Hygienist.

4.1.2 Flammability Testing

Flammability testing was performed to evaluate potential explosion or flammability hazards associated with fiber laser coating removal of specialty materials when common aircraft fluids are present. The fluids tested included Engine Lubricating Oil MIL-L-23699 and MIL-PRF-7808, Hydraulic Fluid MIL-PRF-83282 and MIL-H-5606, and JP-8 Turbine Fuel plus Turbine Fuel additive +100.

The flammability results showed no fire or explosion hazards for any weapon system test panel under any test condition or test fluid used. These results were reported in the "Safety and Occupational Health Test Report" (Reference 4).

4.1.3 Air and Wipe Sampling for Chromium Analysis

The air and wipe sampling results were analyzed by Bureau Veritas and are reported in Table 16. All air sample result concentrations were **below detectable limits** and the reporting limit.

Table 16. Chromium Air Sampling Results

Contaminate	Sample Location	Permissible Exposure Limit (mg/m^3)	Reporting Limit Weight (μg)	Baseline Air Sample Concentration (mg/m^3)	Laser Air Sample Concentration (mg/m^3)
Chromium	TEKA Exhaust	0.05	<1	<0.016	<0.016
	Test Cell			<0.015	<0.016
	Operator			N/A	<0.045
Hexavalent Chromium	TEKA Exhaust	0.005	0.01	<0.000081	<0.000081
	Test Cell			<0.000077	<0.000079
	Operator			N/A	<0.000230

N/A = not applicable – no baseline sampling completed; μg = micrograms; mg/m^3 = milligrams per cubic meter.

The air samples for the operator who entered the work cell at the conclusion of stripping operations was significantly under the PEL for chromium and hexavalent chromium. The PEL is the limit of exposure to a chemical substance or physical agent OSHA allows an employee to be exposed to over a Time Weighted Average (TWA). The TWA is calculated by taking the employee's exposure multiplied by the number of hours exposed, divided by 8 hours. An example for determining the Chromium TWA is:

$$\text{TWA} = <0.045 \text{ mg/m}^3 \times [1 \text{ hour exposure} / 8 \text{ hours}] = 0.0056 \text{ mg/m}^3$$

The TWA only applies to personal air samples. This does not include area air samples or wipe samples. Table 17 outlined the TWA operator exposure for one hour after the laser stripping was conducted.

Table 17. Operator Air Sampling Results

Contaminate	Sample Location	PEL (mg/m^3) for 8 hour TWA	Laser Air Sample Concentration (mg/m^3)
Chromium	Operator	0.05	<0.0056 TWA
Hexavalent Chromium	Operator	0.005	<0.00003 TWA

PEL = Permissible Exposure Limit; TWA = Time Weighted Average; mg/m^3 = milligrams per cubic meter

The results from the wipe sampling testing are reported in Table 18. The wipe samples taken from inside the test cell displayed both chromium and hexavalent chromium as being present in the test cell area. The reasoning behind the decrease in chromium concentration from the baseline to the laser stripping wipe sample particulate would be attributed to the fact that the laser stripping table was not cleaned prior to baseline wipe sampling, thus the baseline wipe samples cleaned away more particulate than after laser stripping operations. The air samples results indicate that chromium and hexavalent chromium particulate settled on work surfaces and was not present in detectable concentration in the air.

Table 18. Wipe Sampling Results

Contaminate	Sample Location	Baseline Wipe Sample ($\mu g/100\ cm^2$)	Laser Wipe Sample ($\mu g/100\ cm^2$)
Chromium	Test Cell	250	240
Hexavalent Chromium	Test Cell	0.32	0.13

$\mu g/100\ cm^2$ = micrograms per 100 square centimeters sample area.

There are no federally established regulatory exposure limits for wipe samples of chromium or hexavalent chromium. Wipe samples are performed to determine the amount (weight) of particulate in a specific area and are reported as the total weight of particulate captured on a 100 square centimeter (cm^2) sample area.

The wipe samples taken from the TEKA hopper area, as shown in Figure 73, as well as vials of the particulate matter, were sent for analysis to the Special Test and Research Lab at WPAFB. The coating powder debris was analyzed using scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS). Both hexavalent chromium and trivalent chromium were detected by both SEM and XPS techniques. The SEM spectra detected chromium levels from 0.4 to 2.4 weight percent. The XPS detected chromium levels from 0.6 to 1.9 atomic percent for a 600 micrometer (μm) diameter sampling area.

Figure 73. Wipe Sample Taken From TEKA Hopper after Laser Stripping

4.2 Evaluation Test Results

4.2.1 Laser Test Results

Coating stack-ups from three different USAF weapon systems were evaluated for laser coating removal. For one of the weapon system, the removal goals were accomplished successfully. For the other USAF weapon systems, the removal goals were, accomplished to the best of the sensor's current control abilities. The majority of the conductive layer could be removed; however, the laser removal process was unable to leave the base primer layer completely intact. As a result, some composite substrate was exposed, but did not appear to be damaged through visual (naked eye) examination. Further refinement of the sensor filters and control is recommended, as well as additional SPA model training prior to the implementation of this system for full aircraft coating removal applications.

For most of the laser coating removal testing, the temperatures recorded during the laser removal did not exceed the 250°F maximum temperature requirement. However, there were some instances where the recorded temperature was around 350°F which occurred on the panels with exposed thermocouples. The substrates did not appear to have any thermal damage, but this would need to be confirmed through substrate material testing. A summary of the maximum substrate temperatures recorded during the laser removal testing is outlined in Table 19.

Table 19. Summary of Substrate Temperatures Recorded During Laser Removal

USAF Weapon System	Average Maximum Temperatures Recorded (°F)	Overall Maximum Temperature Recorded (°F)
1	232	276
2	158	352
3	197	222

The laser removal strip rates were different for the various coating stack-ups and coating removal goals. The strip rates ranged between 0.15 minutes per square feet (min/ft^2) and 9.7 min/ft^2. The strip rates for one weapon system were equal to or faster than targeted strip rate goals. However, the strip rate results for the other weapon systems were equal to or slower than the targeted strip rate goals. Updated sensor control capabilities and further optimization testing activities should improve the laser removal strip rate results. A summary of the strip rate results are outlined in Table 20.

Table 20. Summary of Laser Strip Rate Results

USAF Weapon System	Baseline Depaint Process Strip Rates (min/ft^2)	Project Targeted Laser Strip Rates (min/ft^2)	Laser Evaluation Testing Strip Rates (min/ft^2)
1	4.1 – 19.1	0.30 – 0.80	0.15 – 0.66
2	1	0.65	0.55 – 1.80
3	8 – 11	6	7.2 – 9.7

4.2.2 Material Test Results

The material testing outlined below was performed by Northrop Grumman Corporation with assistance from another test facility for the -65°F Conical Mandrel Bend Test.

<u>Coating Lap Shear Adhesion Test</u>

The Coating Lap Shear Adhesion test was performed in accordance with ASTM D1002 and test plan requirements. Five samples were tested at three test temperatures (-65°F, room temperature, and 275°F) for three panel conditions, as listed below, for a total of nine sets of five samples:

- Partially laser stripped panels restored to original topcoat thickness
- Complete laser stripped panels restored to original topcoat thickness
- Control panels in “as painted” condition

The test results for room temperature and -65°F for the partial and full laser strip specimens met or exceeded the control sample results indicating no impact of the laser strip process to coating adhesion. Test irregularities at 275°F caused inconsistent results at each removal method producing inconclusive data.

<u>Coating Conical Mandrel Bend Test</u>

The coating conical mandrel bend test was performed in accordance with ASTM D522. Five samples were tested at two test temperatures (-65°F and room temperature) for two panel conditions, as listed below, for a total of four sets of five samples:

- Partially laser stripped panels (tested as laser stripped – not restored)
- Control panels in “as painted” condition

The panels were examined for any cracks or loss of adhesion using a 10x magnifier. No cracking or adhesion loss was noted on any of the samples tested at room temperature. There was cracking on all the samples tested at -65°F. The associated cracking at -65°F temperature was a secondary failure of the primer which has a lot less elongation than the topcoat material. The test laboratory reported that the -65°F test results showed that the laser stripping had no effect on the topcoat material after the laboratory reviewed previous historical mandrel bend data at -65°F for this same topcoat.

Coating Tensile and Elongation Test

The topcoat tensile and elongation test was performed in accordance with ASTM D412. Two topcoat free films were fabricated for testing: Film 1 was used as a control, and Film 2 was partially laser stripped and tested in that condition. Five samples were tested at each of the three test temperatures (-65°F, room temperature, and 275°F) for of the two panel conditions:

- Partially laser stripped panel (tested as laser stripped – not restored)
- Control panel in "as painted" condition

Peak stress and elongation test results at -65°F for the partial laser strip samples were similar to the control. The peak stress results for the partially laser stripped specimens at room temperature and 275°F averaged approximately 14% and 20% lower that the controls respectively. The SPO will need to determine if the peak stress results for the partially laser stripped samples for the room temperature and 275°F test conditions are acceptable or not

Special Characteristics Test

The Special Characteristics Test evaluated the electrical performance of two panels: partially laser stripped topcoat panel that had been restored to full thickness and a control panel in an "as painted" condition. Data analysis indicated that the control panel passed only 6 of 24 test points (18 failed). The partially laser stripped panel with restored coatings passed all 24 test points.

5.0 CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH / IMPLEMENTATION

The overall objective of this four-year SERDP Project WP-2146 was to develop a laser coating removal process for large-scale removal of specialty coatings and treatments for DoD weapon systems. This objective was accomplished for some coatings, but not others. Testing determined that laser removal is not the appropriate de-paint solution for some specialty materials and stack-ups. For the specialty materials where laser removal is not an appropriate solution, further development of the sensor control systems is required prior to implementation of a robotic laser coating removal system.

Full Aircraft Robotic Laser Coating Removal Systems have been developed for OO-ALC for depainting fighter size and cargo size aircraft and are currently being implemented and transitioned for production use. The spectral, color and thickness sensors could be incorporated onto the robotic laser systems to effectively remove some of the specialty coatings.

The material test results met or exceeded the control sample results indicating no impact of the laser strip process to coating properties such as adhesion, cohesion, elasticity, and special characteristics. There was some degradation in the coating tensile and elongation; however, the weapon system program office will need to determine if this decrease in within allowable limits. Prior to implementation of a robotic laser system, full validation testing as directed by each weapon system program office may be required.

Future implementation of a full aircraft laser coating removal system showed a significant cost savings for various depaint scenarios. When comparing the automated laser removal process to a full aircraft hand sanding process, the laser process was projected to save the depot facility approximately between $3.7 million and $7.4 million annually, depending on production schedules, and provide a capital investment payback period of about 1.4 years.

Occupational health and safety testing was performed to assess inhalation threats, contact threats and flammability/explosion threats of the robotic laser stripping operation. Air sampling results showed that all the contaminants tested were below the detection limit of the analyzing instrument and well below OSHA's PEL. Therefore, the robotic laser stripping operations, performed at CTC ETF, do not pose any significant inhalation threat to operators entering the work area at the conclusion of laser stripping operations.

Wipe sample results showed elevated levels of chromium and hexavalent chromium on work surfaces in the work cell; therefore, proper PPE (i.e., eye protection and gloves) should be worn when handling panels or aircraft surfaces after stripping operations of chromium contained coatings.

Spectral analysis of the coating debris showed that it contained both chromium and hexavalent chromium; therefore, the coating debris would be classified as hazardous waste and anyone handling the debris would need to wear appropriate PPE (i.e., coveralls, respirators, gloves, and eye protection).

The flammability results showed no fire or explosion hazards for any weapon system test panel under any test condition or test fluid used. Therefore, robotic laser stripping operations do not pose any significant flammability or explosion threat when operating under normal conditions.

These occupation health results overall prove that engineering controls in place (vacuum on laser) are sufficiently removing majority of particulate at the point of operation. Additional occupational health and safety testing would be required for each laser coating removal production environment to ensure the engineering controls are working properly and to determine the appropriate PPE for the operators.

LIST OF ACRONYMS AND ABBREVIATIONS

°F	Degrees Fahrenheit
μg	Micrograms
μm	Micrometer
AFRL	Air Force Research Laboratory
ARL	Army Research Laboratory
ARLCRS	Advanced Robotic Laser Coating Removal System
CBA	Cost Benefit Analysis
cm^2	Square centimeter
CO_2	Carbon Dioxide
COTS	Commercial-off-the-shelf
CTC	Concurrent Technologies Corporation
DoD	Department of Defense
ETF	Environmental Technology Facility
kW	Kilowatt
mg/m^3	Milligrams of pollutant per cubic meter of ambient air
mm	Millimeters
N/A	Not applicable
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
NIOSH	National Institute for Occupational Health
nm	Nanometer
NREC	National Robotics Engineering Center
OO-ALC	Ogden Air Logistics Complex
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PPE	Personal Protective Equipment
ppm	Parts per Million
RCRA	Resource Conservation and Recovery Act
RXSS	Materials Integrity Branch; Systems Support Division; Materials and Manufacturing Directorate
SEM	Scanning Electron Microscopy
SEM	Surface Emissions Monitor
SERDP	Strategic Environmental Research and Development Program
SON	Statement of Need
SPA	Surface Property Analyzer
SPO	System Program Office
TWA	Time Weighted Average
USAF	United States Air Force
WPAFB	Wright Patterson Air Force Base
XPS	X-Ray Photoelectron Spectroscopy